32855 02 8608

32855 02 8608

CDC 32855

AIRBORNE COMMAND POST COMMUNICATIONS EQUIPMENT SPECIALIST

NEWARK PUBLIC LIBRARY

SEP 8 1996

U. S. GOVT. PUBS.
DEPOSITORY 378

(AFSC 32855)

Volume 2

Electronic Fundamentals and Electron Tube Circuits

Extension Course Institute
Air University

D 301.26/17 2

Prepared by
MSgt Sven E. Barkman

Reviewed by
Alfred B. Hill

Edited by
Joyce G. Grimes

3300 TECHNICAL TRAINING WING (ATC)
KEESLER AIR FORCE BASE, MISSISSIPPI 39534-5000

EXTENSION COURSE INSTITUTE (AU)
GUNTER AIR FORCE STATION, ALABAMA 36118-5643

Preface

THIS SECOND volume of CDC 32855 is an introduction to electronic fundamentals and electron tube circuits. The first chapter covers DC circuits, magnetism, relays, and meter movements. Chapter 2 deals with AC circuits, generators, inductance, and capacitance. The third chapter introduces vacuum tubes and various vacuum-tube circuits. Our goal here is to equip you with the basic electronic knowledge to become a competent specialist and later, technician.

Code numbers on figures are for preparing agency identification only.

The inclusion of names of any specific commercial product, commodity, or service in this publication is for information purposes only and does not imply indorsement by the Air Force.

To get an *immediate response* to your questions concerning subject matter in this course, call the author at AV 868–2084 between 0800 and 1600 (CT), Monday through Friday. Otherwise, write the author at 3380 TCHTG/TTGU–C, Keesler AFB MS 39534–5000, to point out technical errors you find in the text, Volume Review Exercises, or Course Examination. Sending subject matter questions to ECI slows response time.

NOTE: Do not use the Suggestion Program to submit changes to this course.

Consult your education officer, training officer, or NCO if you have questions on course enrollment or administration, Your Key to a Successful Course, and irregularities (possible scoring errors, printing errors, etc.) on the Volume Review Exercises and Course Examination. Send questions these people can't answer to ECI, Gunter AFS AL 36118–5643, on ECI Form 17, Student Request for Assistance.

This volume is valued at 24 hours (8 points).

Material in this volume is reviewed annually for technical accuracy, adequacy, and currency. For SKT purposes the examinee should check the Index of ECI Study Reference Material to determine the correct references to study.

Contents

Chapter		Page
	Preface	*iii*
1	Direct Current	1
2	Alternating Current	24
3	Tubes and Electronic Circuits	46
	Bibliography	93
	Answers for Exercises	94

Direct Current

APPLICATIONS of electricity from the simplest appliance to the most complicated piece of equipment are based on the fundamental principles of electricity. This chapter will explain the more important fundamentals, those which you will need to study this CDC. This chapter presents basic concepts of electricity and magnetism, describes the behavior of direct current in a variety of circuits, and presents formulas and equations that you will use in your job.

1-1. Principles of Direct Current

Your job as a maintenance specialist is directly related to DC principles, and this section reviews those principles. You will also study resistive circuits, magnetism, relays, and meter movements.

200. State basic electronic principles and characteristics of common electrical components.

Electron Theory. The smallest particle into which any substance can be divided and still retain its characteristics is the *molecule*. A molecule is built of atoms. A molecule of water, for example, is made up of two hydrogen atoms and one oxygen atom. A substance that contains only atoms that have the same chemical properties is called an *element*. Oxygen is an element, since it contains only oxygen atoms. Likewise, nitrogen is an element because it is composed only of nitrogen atoms. There are over 100 elements known to science. In addition to the elements occurring in a natural state, scientists have synthesized many more. The atom itself consists of protons, electrons, and various particles. The proton has a *positive* charge of electricity, and the electron has a *negative* e charge of electricity. The atom's nucleus holds the protons, neutrons (another type of particle consisting of protons and electrons), and other particles with special qualities. The electrons spin around this nucleus the same way the planets move in orbit around the sun.

One of the fundamental laws of electricity is that *like* charges repel each other, and *unlike* charges attract each other. This law explains the bond that exists in the atom between the positively charged nucleus and the electrons revolving about the nucleus. The orbits of the electrons within an atom differ. Some electrons are close to the nucleus; others are far away. Electrons in the outer orbit are loosely bound and, when influenced by outside forces, may be torn away from the nucleus, leaving the atom with a deficiency of electrons. The atom is then a positive atom and is called an *ion*. The electrons that are loosely bound to the nucleus are called *free* electrons and exist in greater numbers in the atoms of some elements than in others. Metals contain more free electrons than such substances as rubber and glass.

Electrical Potential, Conductors, Insulators, and Semiconductors. When a metal bar or wire is connected between two points with more electrons at one point and fewer electrons at the other point, there is a potential for the flow of free electrons. The greater the difference in the number of electrons, the greater the potential and the greater the amount of electron flow. In addition to the electrical potential, the amount of electron flow depends on the physical characteristics of the conductor. A substance that contains many free electrons, such as metal, is called a conductor and offers little opposition to the flow of electrons. Glass, which has a few free electrons, is called an insulator and offers great opposition to electron flow. Actually, there is no perfect conductor nor perfect insulator. A substance is a good conductor or a poor conductor; an insulator is a good or poor insulator. There is also a classification called semiconductors. Such substances as germanium or silicone, whose conduction is poor in its pure form, are improved by the addition of certain substances. You will learn how these substances are used in transistors.

Resistors. A resistor is a circuit element designed to offer a certain amount of opposition to current flow. Some resistors are sections of carbon rod or some combination of carbon and other substances molded into cylindrical form. Others are wire wound, which makes possible the manufacture of a precise resistance. Wire-wound resistors are capable of carrying, without damage, heavier current than carbon resistors. Another characteristic of resistors is their power rating. Power rating indicates the maximum current that can flow through the resistor without burning it out.

A colored band, or some other arrangement of colors, indicates the resistance value of the resistor. Every resistor is marked with a value along with a percent of tolerance. Carbon resistors usually have a tolerance of 5, 10, or 20 percent; wire-wound resistors can have a tolerance as low as 1 or 2 percent. A 2000-ohm resistor with a 10-percent tolerance, for example, has an actual value of 2000 ohms plus or minus 10 percent, or a range of 1800 to 2200 ohms. Although this may seem like a wide range of values, most circuits operate if the circuit components are within 10 percent, or even 20 percent, of the desired value. Where precision is required, resistors of lower tolerance are used.

In the circuit problems in this text, we assume the value of resistance to be exact and do not require you to consider tolerance unless otherwise indicated.

Some circuits require a resistor that can be varied between limits. Variable resistors are either tubular or circular, with one movable contact. In the circular form, the movable contact is connected to a shaft, which moves the contact along the arc of the resistor. This type of resistor may be made of carbon or wound wire. Wire-wound tubular resistors are designed to carry large amounts of current. They have a sliding strap contact to vary the amount of resistance.

Exercises (200):

1. State the law of like and unlike electrical charges.

2. What characteristics of a substance make it a good conductor?

3. What characteristics of a substance make it a good insulator?

4. Why is a resistor used in a circuit?

5. What type of resistor should you use for a tolerance of 1 percent?

6. What is the maximum tolerance a carbon resistor can have?

201. State Ohm's law, Kirchhoff's laws, and the relationships among current, voltage, resistance, and power.

Electromotive Force. The force that produces a flow of electrons is known as electromotive force (EMF), potential difference, or voltage. All of these terms mean the same thing and are used interchangeably. The unit of measurement of electromotive force is the volt, which is the amount of electrical pressure required to maintain a current of 1 ampere through a resistance of 1 ohm. Another term related to electromotive force is voltage drop. This is the voltage measured across each of the resistances to electron flow in a circuit.

Current Flow, Resistance, and Power. *Current* is the movement of electrons through a conductor. The total amount of charge transferred by moving electrons is measured in coulombs or fractions of coulombs. The rate at which they flow is measured in amperes. (Ampere is often abbreviated "amp.") . An ampere is equal to 1 coulomb per second flowing past a given point, roughly the current flowing in a 100-watt lamp. The opposition a conductor (or insulator) offers to the flow of electrons is called *resistance*. The resistance of a conductor depends on the cross-section area, the length, and the relative resistance of the material. The unit of resistance of electron flow is the ohm. The relation between the volt, the ampere, and the ohm is known as *Ohm's law*. It states that, in any circuit, or part of a circuit, the current in amperes is equal to the EMF divided by the ohms. Mathematically, this is stated as $I = E/R$, or $E/R = I$, where I represents the current in amperes, E represents the voltage in volts, and R the resistance in ohms. Other ways of stating this formula are $E = IR$ and $R = E/I$.

Power is the rate of doing work. The watt is the unit of electrical power and is equal to work done at the rate of 1 joule per second. (A joule is the practical metric unit of work.) One joule equals 1017 ergs (the basic unit of work). Power in an electrical circuit is the product of voltage and current, expressed by the formula $P = EI$, where P equals the power in watts, I the current in amperes, and E the EMF in volts. Since, according to Ohm's law, $E = IR$, this equation can also be written $P = I^2R$. Since $I = E/R$, the formula can also be written $P = E^2R$. You will use all three formulas often.

Kirchhoff's Laws. Sometimes Ohm's law is inadequate for solving complex series-parallel circuits, especially those in which you cannot easily determine the direction of current flow. Kirchhoff's laws are simple to state, but applying them is sometimes difficult. Briefly, the Kirchhoff's laws state that the algebraic sum of the currents at any junction of conductors is zero, the amount of current entering a junction point must be equal to the amount leaving it, and the algebraic sum of the applied voltages and the voltage drops around any closed circuit is zero.

Exercises (201):

1. Give the three terms for EMF.

2. What unit measures EMF?

3. What units measure resistance, current, and power?

4. Define the term "watt."

5. State the three aspects of Kirchhoff's current law.

202. Differentiate between DC resistive circuits and use Ohm's law to solve for values of current, power, and voltage.

Series Circuit. The simplest electrical circuit is the series circuit, where current flow is the same at all points (fig.1-1). The arrows indicate the direction of current flow. At the positive terminal of the battery, there is a deficiency of electrons, while at the negative terminal there is a surplus. The battery's EMF forces electrons to flow through the circuit in the direction indicated, from the negative terminal to the positive terminal.

To find the *current* in the series circuit in figure 1-1, use the Ohm's law formula, I = E/R. The applied voltage E is 100 volts, and resistor R's resistance is 2000 ohms. When we substitute these quantities in the formula, we have $I = \frac{100}{2000}$, or 0.05 ampere. When this current flows through R, *power* is expended. To find the power expended, we substitute in the power formula $P = I^2R$ to $P = 0.05^2 \times 2000$, or 5 watts.

The circuit in figure 1-2 has three resistors connected in series, and the current in the circuit flows through each resistor in succession as well as through the ammeter, represented by a circled A. The circled V represents a voltmeter. A voltmeter must always be connected in parallel with that part of the circuit developing the voltage to be measured. Voltmeters can be used to measure the EMF of a battery, or the voltage drop across a resistor, or across other circuit elements. Now let's calculate the current flow and the power rating of each resistor in figure 1-2 with the values shown. Since all the current flows through each resistor, the total resistance is the sum of the individual resistors: $R_t = R1 + R2 + R3$, or $R_t = 1000 + 2000 + 5000$, which is 8000 ohms. The **total current** is I = E/R, or $\frac{100}{8000}$, which is 0.0125 ampere.

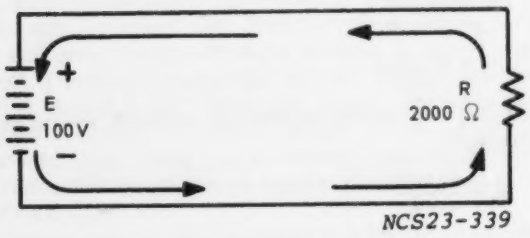


Figure 1–1. Series circuit.

Because the ampere is rather a large unit, current is usually measured in *milliamperes* (mA)—thousandths of an ampere—or in *microampere* —millionths of an ampere. To find the power rating of each resistor, substitute in the power formula $P = I_2R$.

$P1 = 1^2 \times R1 = (0.0125)^2 \times 1000 = 0.15625$ watt
$P2 = 1^2 \times R2 = (0.0125)^2 \times 2000 = 0.3125$ watt
$P3 = 1^2 \times R3 = (0.0125)^2 \times 5000 = 0.78125$ watt

The total power used by the battery is the sum of the power used by the individual resistors: 0.15625 + 0.3125 + 0.78125, or 1.25 watts. It is also the total voltage multiplied by the total current: $P_t = E_t \times I_t$, so $P_t = 100 \times 0.0125 = 1.25$ watts. To find the **voltage** across each resistor, apply the formula E = IR:

$E1 = I \times R1 = 0.0125 \times 1000$, or 12.5 volts
$E2 = I \times R2 = 0.0125 \times 2000$, or 25 volts
$E3 = I \times R3 = 0.0125 \times 5000$, or 12.5 volts

The sum of the voltages across the three resistors is 100 volts, which is the applied voltage. In any series circuit, the sum of the voltages across the individual resistors is always equal to the applied voltage.

When current flows through a resistance, it produces a potential difference between the terminals of the resistor. The amount of voltage is found by applying Ohm's law to the circuit. The polarity of the voltage drop across a resistor is due to the current flow through it. The current flow is through R3, R2, R1, and back to the positive terminal of the battery. The polarity of the voltage drop across R1 makes the left end of R1 (Z) positive with respect to the right end (Y). The voltage drop across R2 is positive at the top with respect to the bottom, and the polarity of the voltage drop across R3 makes point X positive with respect to point W. This method of figuring the polarity of voltage drops across circuit components is important when you connect a voltmeter across a component to measure the voltage.

Voltage Dividers. Resistors connected as they are in figure 1-2 are a voltage divider network. This type of circuit is useful for providing voltages of different values. For example, if we need 25 volts, we can get it across R2. We can use a potentiometer to make a voltage across a resistor variable between fixed limits. A potentiometer is like a variable resistor with connections at both ends. A movable contact lets us vary the resistance. Figure 1-2,b, is a circuit with a potentiometer. In this circuit, the potential at the bottom of R2 is 62.5V; the potential at the top is 87.5V. By moving the center top of R2, you can apply any voltage between these two potentials to another circuit.

Parallel Circuits. In the parallel circuit shown in figure 1-3, the terminals of resistors R1, R2, and R3 are joined together at points X and Y. Current divides at point X, with part of it going through each resistor. The individual currents combine at point Y and flow to the positive terminal of the battery. The voltage across each of the three resistors equals the battery voltage of 100 volts. To find the total *current* supplied by the battery to the combination of

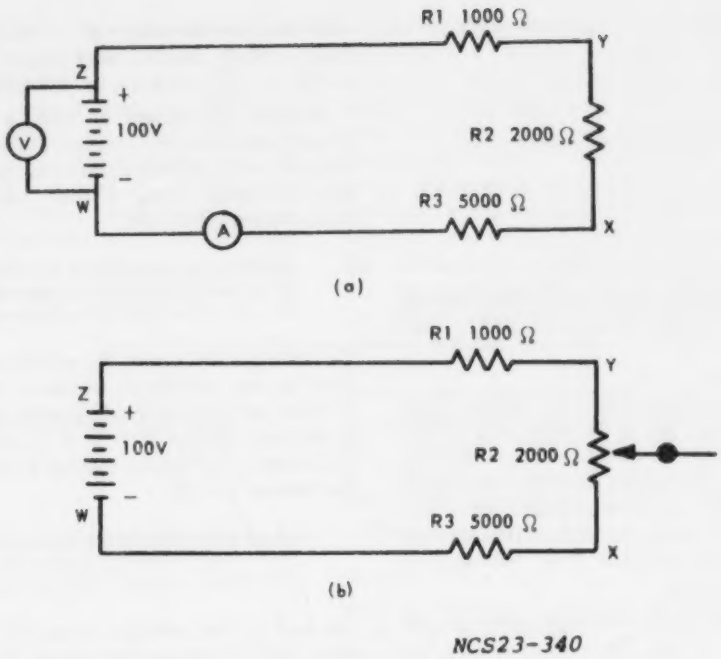


Figure 1–2. Series circuit.

parallel resistors, first find the current through each individual resistor and then find the sum of the individual currents. Applying Ohm's law formula I = E/R, we find that R1 = 0.1 ampere, R2 = 0.05 ampere, and R3 = 0.02 ampere. The total *power* expended by the battery is the sum of the power expended in each resistor. Using the power formula P = EI, we find that R1 = 10 watts, R2 = 5 watts, and R3 = 3 watts. When you know the total current, you can find the total, or equivalent, *resistance* in a parallel circuit by the Ohm's law formula R = E/I. The equivalent resistance in the circuit of figure 1-3 is:

$$R_e \text{ (equivalent)} = \frac{E_t}{I_t}$$

$$R_e = \frac{100}{0.17}$$

$$R_e = 588 \text{ ohms}$$

Note that this equivalent resistance is less than that of the individual resistors R1, R2, and R3. The equivalent resistance of two or more resistors in parallel is always less than that of any of the resistors alone. In the circuit shown in figure 1-3, you can solve for the total resistance by using the formula:

$$\frac{1}{R_e} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3}$$

$$\frac{1}{R_e} = \frac{1}{1000} + \frac{1}{2000} + \frac{1}{5000}$$

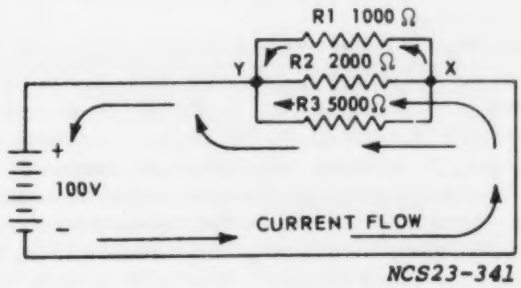


Figure 1–3. Parallel resistors.

$$\frac{1}{R_e} = 10 + 5 + \frac{2}{10,000} = \frac{17}{10,000}$$

$$R_e = \frac{10,000}{17}$$

$$R_e = 588 \text{ ohms.}$$

When only two parallel resistors are involved, we can use the equation

$$R_e = \frac{R1 \times R2}{R1 + R2}$$

The equivalent resistance of two parallel branches is the product of the two resistors divided by their sum. When

there are three or more branches, you can use this formula by combining resistors two at a time until you get a single equivalent resistance. When two equal resistors are connected in parallel, the combined resistance of the two resistors equals one-half of either resistor. The total resistance of three equal resistors in parallel is one-third the resistance of one resistor.

The reciprocal of resistance is *conductance*, which is the property of a conductor that makes it possible for current to flow. It is represented by the letter G. The unit of conductance is the *mho* (ohm spelled backward). For example, the conductance of a conductor with a resistance of 1000 ohms equals 0.0001 mho (1000 micromhos), since $G = \frac{1}{R} = \frac{1}{1000}$. The total current in a parallel circuit divides between the resistance branches. Each branch current is proportional to the conductance in that branch or inversely proportional to the resistance of that branch.

Series-Parallel Circuits. Often you'll find circuits with combinations of resistors in series and in parallel. To solve problems of this type, apply the principles you learned for circuits with resistors only in series and those with resistors only in parallel. As an example, let's look at the circuit in figure 1-4 and find the total current, the current through the 10-ohm resistor, and the voltage drop across the 5-ohm resistor.

First we use the formula to find that the equivalent resistance (R_e) of the 10-ohm and the 15-ohm resistors in parallel is 6 ohms. Since R_e is now in series with the 5-ohm resistor, $R_t = 6 + 5 = 11$ ohms, and the total current is 10 amperes. We can find the part of the total current flowing through the 10-ohm resistor by the formula:

$$I = I_t \times \frac{R2}{R1 + R2}$$

$$I = 10 \times \frac{15}{10 + 15}$$

$$I = 10 \times \frac{15}{25} \text{ or } 6 \text{ amperes}$$

Now we can find the voltage drop across the 5-ohm resistor by the formula: $E3 = I_t \times R3$; therefore, $E3 = 10 \times 5$, or 50 volts.

Resistive Bridge Circuits. Bridge circuits are frequently used in electronics where a signal from one device controls another device. Some bridge circuits have fixed components, while others have variable components, as in very accurate test equipment. We'll keep our discussion to resistive DC bridge circuits. Figure 1-5 shows a parallel circuit with which we are already familiar. It has two paths for current flow. Note the two identifying points on the circuit: point A between resistors R1 and R2, and point B between resistors R3 and R4. Suppose you take points A and B and stretch the circuit. The result is a diamond shape. To make a bridge circuit out of this diamond shape, some type of resistive load (the detecting device) must be connected between points A and B, as shown in figure 1-6.

Perhaps you can see a relationship in the circuit already. If there is a difference of potential between points A and B, current will flow through the load device. The direction depends on the polarity of voltage at point A with respect to point B. On the other hand, if there is no potential difference between points A and B, no current will flow through the load device. Quite often, when the bridge circuit is used in electronic test instruments, the load device is a very sensitive meter movement. Figure 1-7 shows a

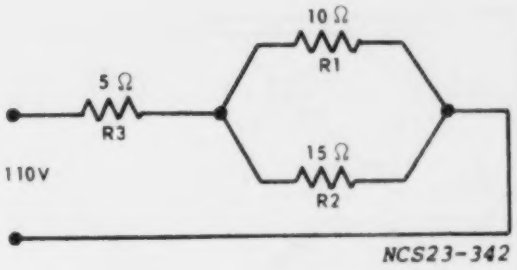


Figure 1-4. Series-parallel circuit.

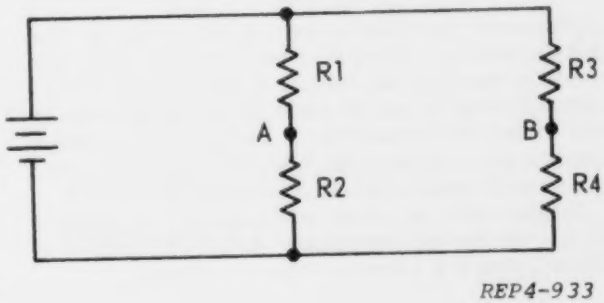


Figure 1-5. Parallel circuit.

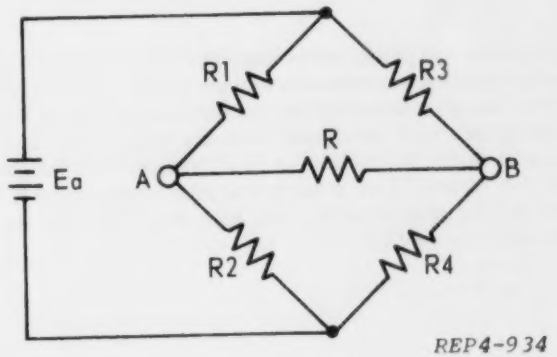


Figure 1-6. Bridge circuit.

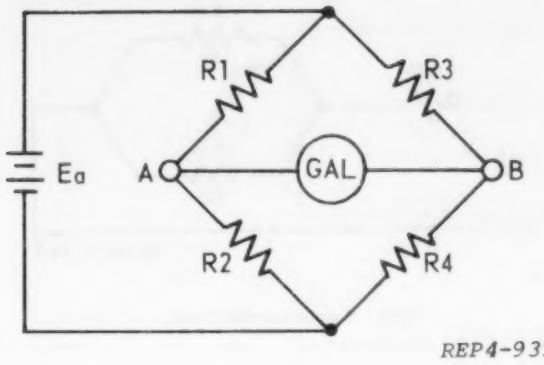


Figure 1-7. Bridge circuit.

galvanometer connected between points A and B. The galvanometer is a sensitive current-indicating meter that measures magnitude and direction of current flow. With no current flowing through the meter, the needle will point to zero. When the galvanometer is reading zero, the bridge circuit is said to be *balanced*. When the bridge is balanced, there's no difference of potential between points A and B.

To show that the circuit in figure 1-8 is a balanced bridge, use the *ratio relationship*—R1 is to R2 as R3 is to R4, or 2 ohms is to 4 ohms as 3 ohms is to 6 ohms:

$$\frac{R1}{R2} = \frac{R3}{R4}$$

$$\frac{2\Omega}{3\Omega} = \frac{4\Omega}{6\Omega}$$

and

$$\frac{2\Omega}{4\Omega} = \frac{3\Omega}{6\Omega}$$

Another way to find out whether the bridge is balanced is to find the potential difference between points A and B (fig. 1-9). You can connect a voltmeter between these points, but instead let's find the answer by using Ohm's law. In a parallel circuit, EA is the same in all branches, but you can see that R1 and R2 are in series with each other and that R3 and R4 are also in series with each other. To find the resistance of branch A:

$$R_A = R1 + R2$$

$$= 2 \text{ ohms} + 4 \text{ ohms}$$

$$= 6 \text{ ohms}$$

To find branch B:

$$R_B = R3 + R4$$

$$= 3 \text{ ohms} + 6 \text{ ohms}$$

$$= 9 \text{ ohms}$$

To find the current through branch A:

$$I_A = \frac{E}{R_A}$$

$$= \frac{18V}{6\Omega}$$

$$= 3 \text{ amps}$$

Current in branch B is:

$$I_B = \frac{E}{R_B}$$

$$= \frac{18V}{9}$$

$$= 2 \text{ amps}$$

To compute the potential at point A and point B, a ground reference point has been added to the circuit shown in figure 1-9. With ground at this point, the potentials at points A and B are positive with respect to ground.

Voltage at point A is:

$$E_A = I_A \times R2$$

$$= 3A \times 4 \text{ ohms}$$

$$= 12 \text{ volts}$$

Voltage at point B is:

$$E_B = I_B \times R4$$

$$= 2A \times 6 \text{ ohms}$$

$$= 12 \text{ volts}$$

Voltage difference between points A and B is 12V − 12V, or 0 volts. With 0 volts existing between the two points, no current will flow through the galvanometer. This is the condition of a balanced bridge.

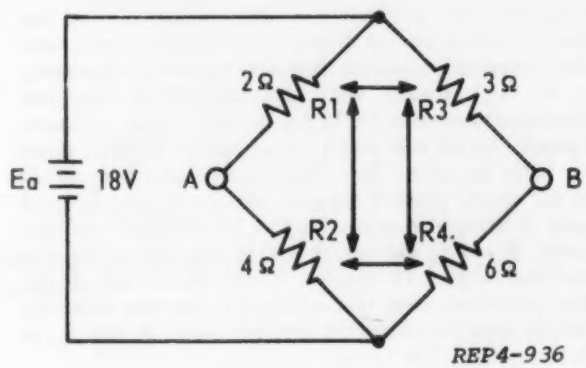


Figure 1-8. Bridge circuit.

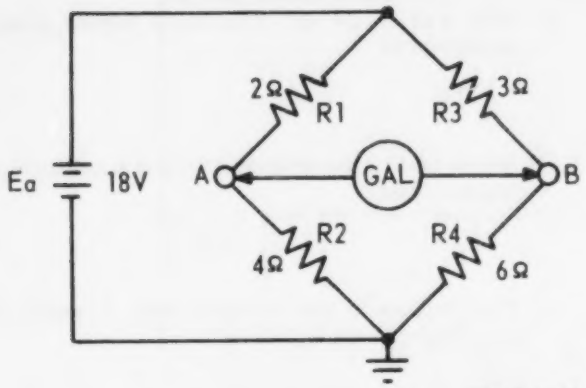


Figure 1-9. Bridge circuit.

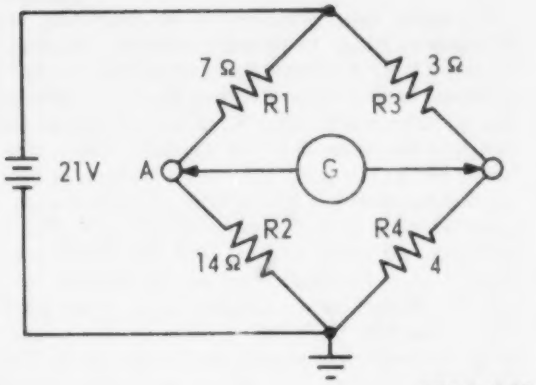


Figure 1-10. Unbalanced bridge circuit.

In these examples, we've been working with a balanced bridge circuit. Now let's look at the characteristics of the *unbalanced* bridge circuit in figure 1-10. To tell whether the bridge is balanced or unbalanced, we use the ratio formula:

$$\frac{R1}{R2} = \frac{R3}{R4}$$

or

$$\frac{7\Omega}{14\Omega} = \frac{3\Omega}{4\Omega}$$

Since 28 does not equal 42, we know the bridge is unbalanced and there's a voltage between points A and B. We can find this voltage by Ohm's law.

Branch A:

$R = 21$ ohms

$$I = \frac{E}{R}$$

$$= \frac{21V}{21\Omega}$$

$= 1$ amp

Voltage at point A:

$E = 1 \times R2$

$= 1A \times 14$ ohms

$= 14$ volts

Branch B:

$R = 7$ ohms

$$I = \frac{E}{R}$$

$$= \frac{21V}{7\Omega}$$

$= 3$ amps

Voltage at point B:

$E = 1 \times R4$

$= 3A \times 4$ ohms

$= 12$ volts

Voltage between points A and B:

$14V - 12V = 2$ volts

Since point A is more positive than point B, current will flow from point B toward point A through the galvanometer. To balance the bridge circuit, we must change the size of R1, R2, R3, or R4. Let's change R4, again using the ratio:

$$\frac{R1}{R2} = \frac{R3}{R4}$$

or

$$\frac{7}{14} = \frac{3}{R4}$$

Solve for R4:

$7 \times R4 = 14 \times 3$

$7(R4) = 42$

$R4 = 6$ ohms

Replace the 4-ohm resistor with a 6-ohm resistor, and the bridge is again balanced. There will be no voltage between points A and B and the galvanometer will read zero.

We apply these principles in an instrument called a Wheatstone bridge to measure unknown resistances. In figure 1-11, R2 is variable and is connected to a dial that is calibrated to read ohms. RX is an unknown resistance. To find the value of RX, adjust R2 until the bridge is balanced, then read the value of R2 on the dial. Why is this true? Notice that R1 is equal to R3. For the bridge to be balanced, R2 must be equal to RX. Therefore, the dial reading of R2 gives the value of the unknown resistor, RX. The largest resistance we could measure with the circuit shown in figure 1-11 is 1 megohm, but we can increase the range with the changes shown in figure 1-12. When RX is less than 1 megohm, place switch S1 in the RA position and adjust resistor RA to balance the bridge circuit. Take the size of RX from the dial reading on resistor RA. With a larger unknown resistor, rotate switch S1 to the right position to measure the unknown value. If the unknown resistor is 900k ohms, for instance, we place switch S1 in the RE position and adjust the 1-megohm resistor for a readout.

Exercises (202):

1. What is the rule for current flow in any series circuit?

2. What is the relationship between individual voltage drops and applied voltage in any series circuit?

3. A voltage divider made up of four resistors is across a 300-volt DC source. The four output tops of the divider are 30 volts, 90 volts, 210 volts, and 300 volts. If the current flow through the divider is 2 mA, what is the value of each resistor in the divider network?

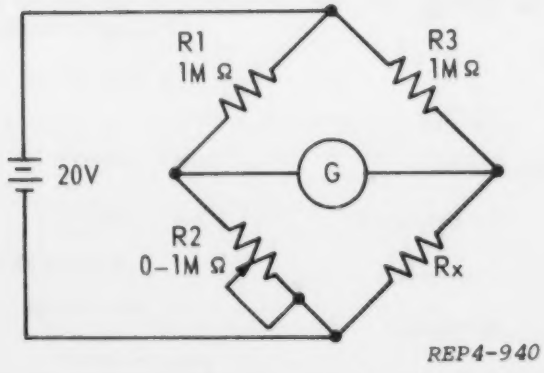


Figure 1-11. Wheatstone bridge.

4. What is always the sum of the branch currents in any parallel circuit?

5. How is total current affected by adding a resistor to a parallel circuit?

6. What happens to total resistance when a resistor is removed from a parallel circuit?

7. What's the equivalent resistance of a parallel circuit with three branches if branch A has only R1 (200,000 ohms), branch B has R2 (75,000) and R3 (225,000) in series, and branch C has R4 (50,000) and R5 (250,000) in series?

8. What calculations must you make before you can find total circuit resistance in a series-parallel circuit?

9. What is conductance?

1-2. Magnetism

You are familiar with magnets in some form. As a child, you may have played with the simple horseshoe-shaped toy magnet and recall how it picked up a nail or small piece of metal. You also are familiar with the simple compass with a magnetized needle that always points *north*. These are two simple examples of magnetism. The principles of magnetism are important in the field of electronics.

203. Cite characteristics of magnetism.

Magnets. A black mineral ore called lodestone, or magnetite, is a natural magnet because, in its natural state, it is already magnetized. Lodestone has very little value as a magnet because of its unstable physical structure and low magnetic strength. Therefore, we have developed artificial magnets made of iron and steel and magnetized by induction from some exterior object, by stroking with some other artificial magnet, or by being placed in the field of an electromagnet. (We'll cover electromagnets later.) A bar of hard steel will hold magnetism for a long period of time, so we call it a permanent magnet. Soft iron can be magnetized easily but loses its magnetism quite rapidly. The effectiveness of a material as a path for magnetic lines of

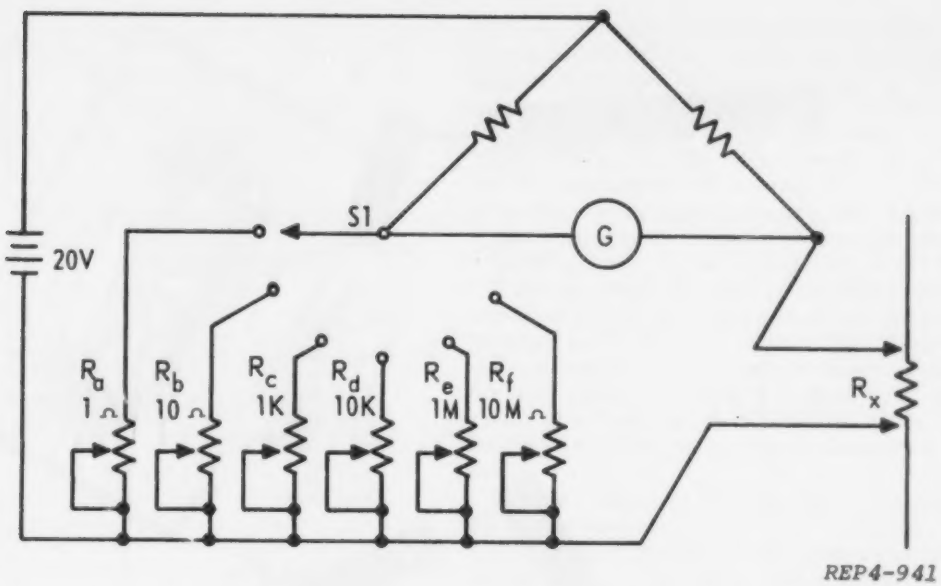


Figure 1-12. Wheatstone bridge.

force is its *permeability*. The property of a substance that causes it to remain magnetized is called *retentivity*, and the magnetism that remains is called *residual magnetism*.

Magnetic poles. When a bar magnet is dipped into iron filings, a large number of filings will cling to the magnet near its ends, but a few will be attracted to the magnet near its center. This indicates that the magnetism is concentrated at the two ends, called the *poles* of the magnet. The magnetic strength of the two poles of any magnet is equal. A magnet free to rotate will always turn to a north-south direction, aligning itself with the earth's magnetic field. The pole of the magnet that turns toward the north is called the north-seeking pole or simply the north pole (N), and the pole at the opposite end is called the south-seeking pole, or south pole (S). If you bring the south pole of one bar magnet near the north pole of another, there will be an attraction between the two poles. If you bring the two north or two south poles together, there will be a force of repulsion between them. The basic law of magnetism states that unlike poles attract each other and like poles repel each other (fig. 1-13).

Magnetic fields. The region around a magnet in which its effect can be detected is its *magnetic field*. At any point near a magnet, the field has a certain direction and intensity. The field of intensity around a pole varies directly with the pole's strength and inversely with the square of the distance from the pole. If you place a sheet of glass over a magnet and sprinkle iron filings over it, you will be able to observe the configuration of the magnetic field (fig. 1-14). Tapping the glass causes the filings to align themselves into chains or lines, producing a "picture" of the magnetic field. The filings actually align themselves along the lines of force of the magnetic field.

The lines of force about a bar magnet travel from the north pole to the south pole (fig. 1-15). They have only one direction at a given point, do not cross each other, and form closed loops. The path of each loop is from the north pole to the south pole in space and through the magnet to the north pole. The total number of lines of force that occupy a region of magnetic activity is called a *magnetic flux*. The number of lines passing perpendicularly through a square centimeter is called *flux density*.

Lenz's law. Heinrich Lenz, in 1834, summed up induction in a law that predicts the direction of induced voltages and currents. Lenz's law states: The electrodynamic action of an induced current opposes the action inducing it. The current flow caused by an induced voltage always creates a flux in a direction that opposes the effect that produced the induced voltage.

Electromagnetism. Current flowing in a conductor causes a magnetic field to surround the conductor. The strength of this field depends on the amount of current flow. The magnetic lines of force about a current-carrying conductor will be either clockwise or counterclockwise, depending on the direction of current flow. You can determine the direction of these lines of force by using the "left-hand rule." (fig. 1-16). If you grasp the conductor with your left hand so that your thumb points in the direction of the current flow, your fingers will indicate the direction of the lines of force. This rule will be used later in this chapter.

Mutual induction. In an electrical circuit, a change of current flow always causes a change in the magnetic field surrounding the conductor. If the current flow increases, the field increases or expands. If current flow decreases, the field decreases or collapses. If a conductor is placed within

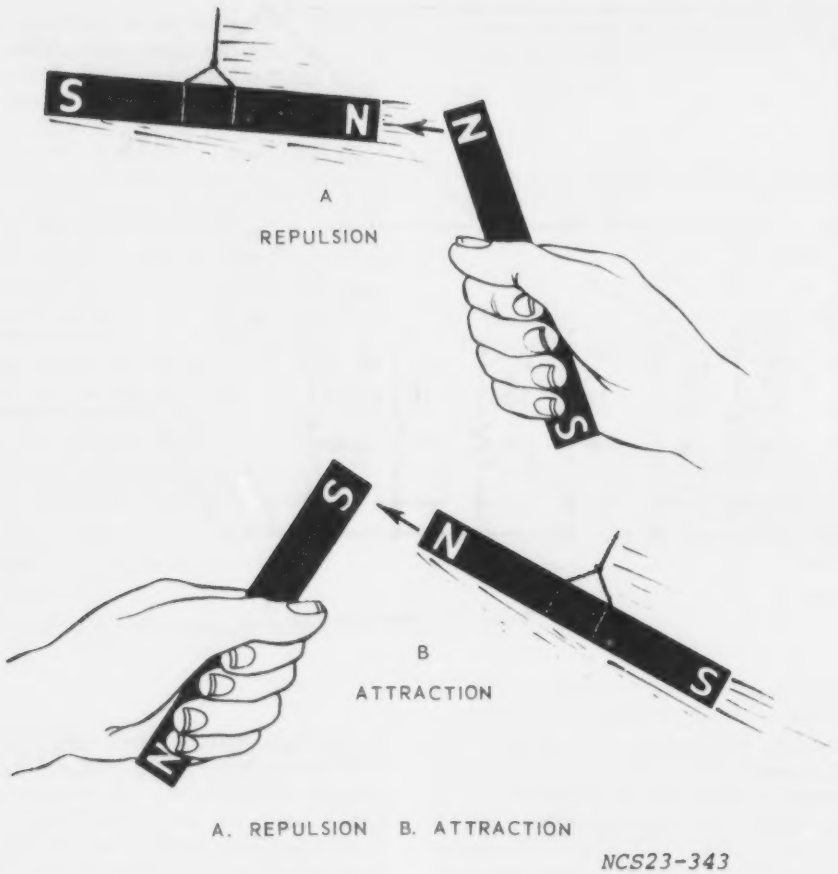


Figure 1-13. Like and unlike poles.

this magnetic field, a voltage will be induced into the conductor. This is the principle of mutual induction.

Exercises (203):

1. How do the terms permeability and retentivity apply to magnetism?

2. What is residual magnetism?

3. What is the reaction when two like magnetic poles are placed together?

4. What determines the direction of the magnetic lines of flux about a wire?

1-3. Relays.

Electromechanical devices are devices that use electromagnetism to operate, one of the simplest of which is the relay. Relays use the magnetic effect produced when a current is applied to a coil to attract an iron bar. This iron bar opens or closes other circuits.

204. State the principle of electromagnetic relays, and specify the use of the given types.

Electromagnetic Relay. While relays are made in many different sizes and shapes and are used for many different purposes, all electromagnetic relays operate on the principle that iron is attracted to a pole of an electromagnet.

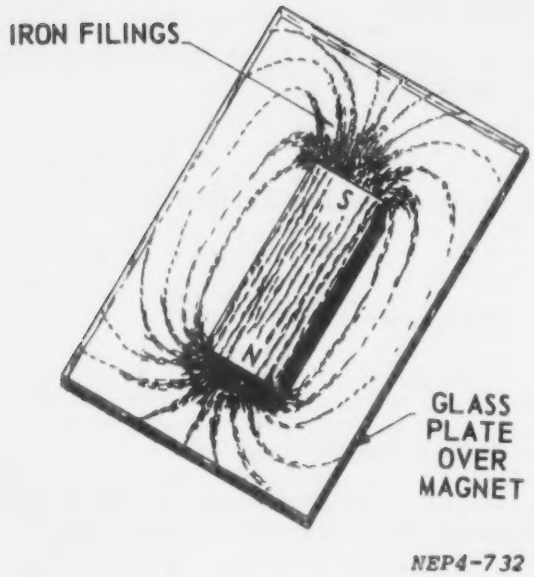


Figure 1-14. Magnetic field.

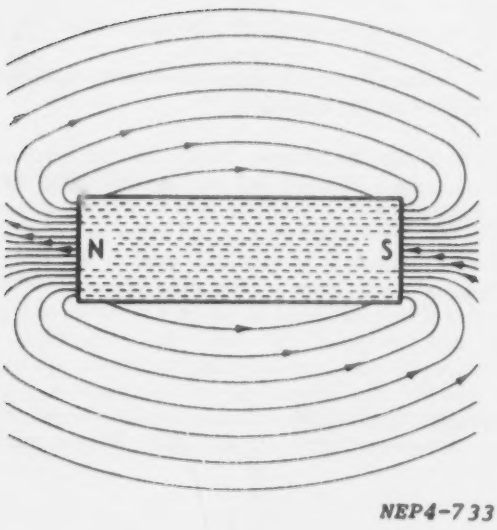


Figure 1-15. Lines of force.

A relay is essentially a coil with an iron core and movable iron bar. When current flows in the coil, electromagnetism pulls the movable bar toward the core, opening or closing a circuit. The relay is usually referred to as a remote control switch because it can control the operation of other circuits without being in the same area. Figure 1-17 shows a basic relay and relay circuit. The relay itself has five main parts: core, coil, armature, contacts, and spring. When switch S is closed, current flows through the coil, setting up a strong magnetic field around the coil. This magnetic field pulls the armature toward the core of the coil, closing the contact point and completing the path for current in the lamp circuit. Closing the relay circuit controls the lamp circuit, and the lamp glows. When switch S is opened, the field about the electromagnet collapses, the spring pulls the armature contacts apart, and the lamp circuit opens.

Holding Relay. In the holding relay circuit of figure 1-18, closing switch S2 lets current flow in coil C. The contact arm (which contains iron) will be attracted toward the upper end of the electromagnet, thus closing the circuit at A and making a complete path for current in coil C and in the lamp circuit. The lamp will glow. Now opening the switch S2 will not open the coil or lamp circuit. To do this, switch S1 must be opened. This is the action of a *holding relay*.

Remote Control, or Starting, Relay. A common use of the relay is in an automobile starter circuit (fig. 1-19). The ignition switch activates a relay that closes to let high current flow in the starter motor circuit. The starter armature rotates and by a gear arrangement rotates the crankshaft. When the ignition switch closes the relay coil circuit, current flows in the coil. The many turns of wire that form the coil offer enough resistance to limit the current to a fraction of an ampere even though the coil is connected directly across the battery. This current causes an electromagnetic force that pulls the iron bar B toward the coil and closes the starter motor circuit. Note that the conductors in this circuit are short, heavy cables. Their

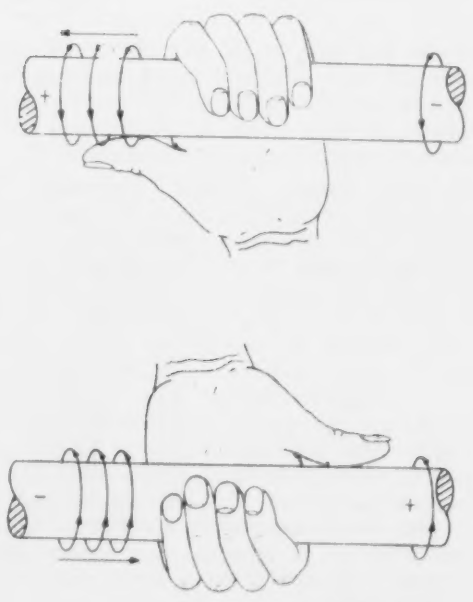


Figure 1-16. Left-hand rule.

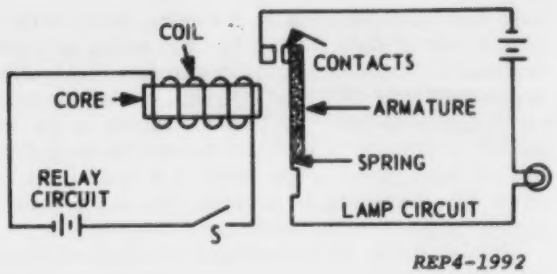


Figure 1-17. Relay circuit.

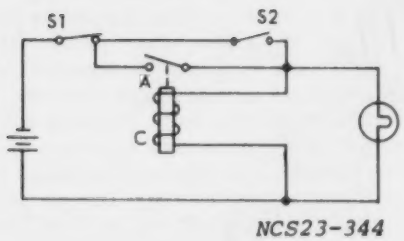


Figure 1-18. Holding relay.

large size and short length decrease the I^2R loss. The expense and weight of a starter circuit that routes the heavy current through the switch on the steering column is prohibitive. A small current in the relay coil circuit can control a very large current in the starter circuit.

Overload Relay. Another application of an electromagnetic relay is its use as a protective device, similar to a fuse (fig. 1-20). When switch S is closed, current flows through the relay coil and load resistor (R_L). Let's assume that normal circuit current is 10 mA and the relay takes 20 mA current through the coil before it will energize. Suppose the load resistor partially shorts out, causing the circuit current to exceed 20 mA. As soon as 20 mA flows through the relay coil, the relay will energize and interrupt the path for current. Once energized, the latch will lock open. After you correct the trouble, you can push the reset button to unlock the armature, which then returns to its normally closed position. This is the action of an *overload* relay with manual reset. More elaborate overload relay circuits often use an automatic reset feature. Electronic systems use many types of relays, and obviously not all are for remote control switching. Regardless of their purpose, the principle of operation is the same: a current through a coil creates an electromagnet, which moves an iron bar to open or close another circuit.

Exercises (204):

1. On what principle do all electromagnetic relays operate?

2. What is a common use of a remote control relay?

3. How is an overload normally used?

1-4. Meter Movements

You'll need to understand the test instruments used in maintaining communications equipment if you are to increase your proficiency and gain the 5-skill level. Let's start with a discussion of the types of meter movements, then move on to analyzing the circuits of ammeters, voltmeters, and ohmmeters. Depending on the electrically produced effect that actuates its mechanism, a meter movement is said to be *electromagnetic*, *electrothermal*, or *electrostatic*. Since the meter movement is the heart of a measuring instrument, let's discuss the construction, operating principles, sensitivity, and accuracy of each type.

205. Compare types of meter movements and specify operational details of meters.

Electromagnetic Meters. Most meters are based on the electromagnetic principle and are classified as permanent-magnet moving-coil, dynamometer, or moving-iron vane. The permanent-magnet moving-coil meter gets most of our attention, because it is so widely used in Air Force test equipment. As its name implies, this type of meter uses a permanent magnetic field to act on a movable coil. As it was first developed in 1882 by D'Arsonval, this galvanometer is an extremely delicate device, not suitable for portable use. Its moving coil is wound on a frame suspended between the poles of a stationary magnet by very fine hard-drawn wires. About 1885, Weston improved

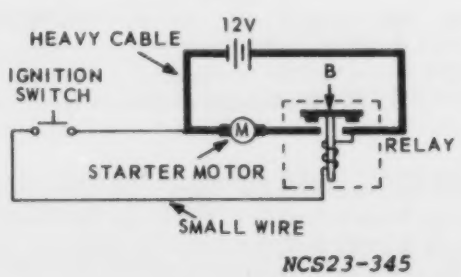


Figure 1-19. Starter relay.

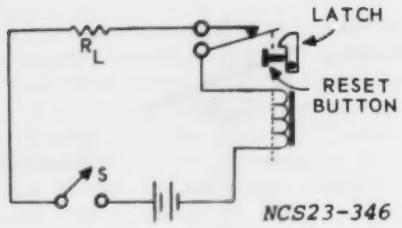


Figure 1-20. Overload relay.

D'Arsonval's galvanometer, developing the Weston movement, which is now universally used in measuring instruments. It is small and meets the conditions of accuracy, ruggedness, portability, and compactness required of electrical instruments for general use. Weston kept the basic idea of the stationary permanent magnet and moving coils and added several structural refinements which eliminated most of the objections to the D'Arsonval meter. The moving coil in the Weston movement is not suspended by wires, but by hardened steel pivots resting in cup-shaped sapphire jewel bearings. This method of support is virtually frictionless and makes the movement practical for portable test instruments.

Figure 1-21 shows the essential parts of the Weston meter. The permanent magnet is fitted with two curved soft-iron pole pieces. A soft-iron cylindrical core is mounted between the pole pieces and adjusted for a uniform air gap between the pole pieces and the core to produce a strong radial magnetic field of constant density (fig. 1-21,A). Within this air gap, a coil of fine wire (wound on an aluminum frame, or bobbin) is supported at top and bottom by pivots that turn in cup-shaped bearings (fig. 1-21,B, and C). Connections between the coil and external terminals are usually made via two spiral torque springs. These springs position the pointer and provide a counter (restoring) torque to the turning of the coil. They are coiled in opposite directions to compensate for variations caused by

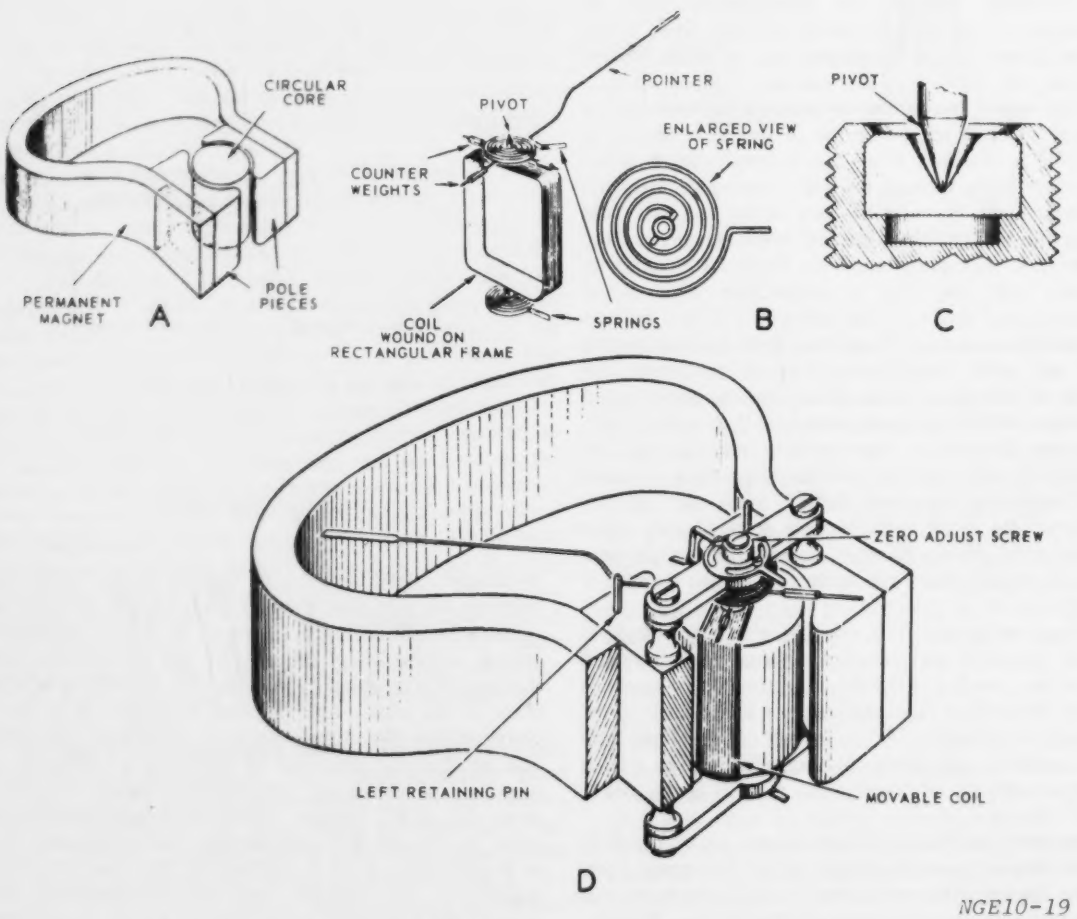


Figure 1-21. Weston meter movement.

temperature and aging. The pointer, which is attached to the bobbin (moving-coil frame), is carefully balanced by small counterweights, letting the pointer hold its zero position very closely, even if the instrument is not level.

Figure 1-21,D, shows an assembled Weston movement. The movement is actuated when current flows through the coil. As you know, the electromagnetic field of the coil interacts with the field of the permanent magnet to produce a turning force, or torque. Because there is a radial magnetic field, the rotation of the coil (which is restrained by the torque springs) is directly proportional to the current. This, of course, means that the deflection of the pointer is also directly proportional to the current. Therefore, the scale used with this type movement is substantially *linear*. Since the direction of deflection depends on the direction of current flow, you must respect polarity. This mechanism responds only to direct current, but it can be used in conjunction with various circuits to make many types of electrical measurements. It can be made extremely sensitive so that a very small current will cause full-scale deflection.

Dynamometers. Figure 1-22,A, shows the essential parts of the dynamometer, or electrodynamometer. Instead of a permanent magnet, the dynamometer uses an electromagnet generally consisting of two fixed coils. Electrical connections to the moving coil, as in the Weston movement, are made via the control (torque) springs. When this meter movement is used in an ammeter or voltmeter, all coils are connected in series, as shown in figure 1-22,B. Current from the external circuit under measurement flows through the coils to produce magnetic fields about them. Because the axis of the magnetic field about the movable coil is not parallel to the axis of the fixed coils, the two interacting magnetic fields try to align in accordance with the laws of magnetism. This action produces a torque that turns the movable coils and deflects the pointer by an amount proportional to the current flowing through the coils. Unlike the Weston movement, the direction of deflection is unaffected by the direction of current flow; therefore, it responds to AC as well as DC. The reason for this is that polarity reversals of the alternating-current source produce corresponding reversals in the interacting magnetic fields. Since the polarity reversals of the fixed coils and the moving coil occur simultaneously, the net result is the same as though there were no reversals; thus, the deflection of the pointer is unchanged.

Moving-iron types. The moving-iron mechanism is designed primarily to measure alternating current at powerline frequencies. Like the dynamometer, it responds to either AC or DC. Its sensitivity is the lowest of the electromagnetic meters, but its simple construction, high current-handling capabilities, and ruggedness make it most suitable where circuit conditions permit fairly heavy loading.

Electrothermal Meters. These meters are actuated by the effect of a temperature change caused by current flow. Since the heating effect of current is used, electrothermal meters require warmup time for a reliable reading. They are sluggish, compared to other meters, and their scale is

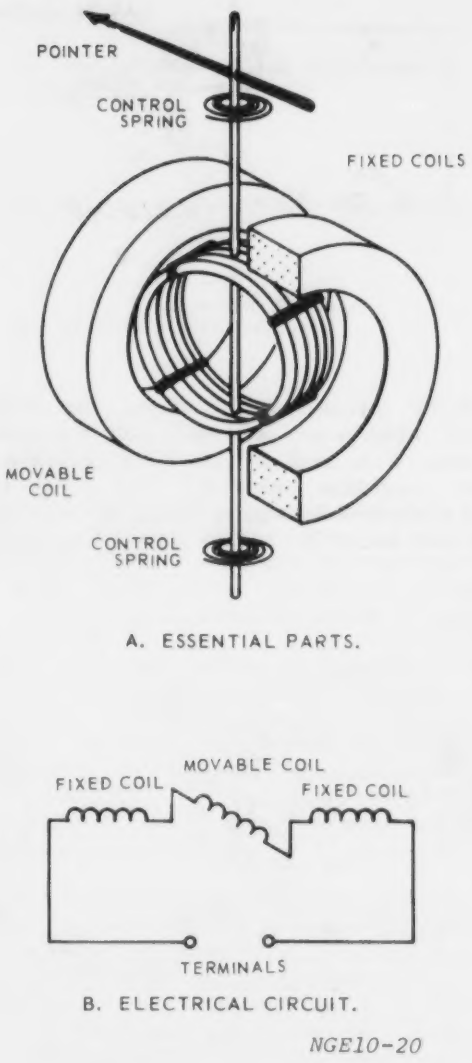


Figure 1-22. Dynamometer.

nonlinear unless they are of special design. Their most common use is in measuring RF (radio-frequency) current.

Electrostatic Meters. Instead of being actuated by current (or the effect of current), the electrostatic meter movement is actuated by voltage. For this reason it is in a class of its own. Its operation is based on a law of electrostatics: like charges repel and unlike charges attract. The charges are produced by applying a voltage to the terminals of the meter. Electrostatic meters respond to either DC or AC voltage. Polarity reversals caused by AC occur on the movable and stationary parts simultaneously, so the actuating force is unaffected. This type meter lacks sensitivity. Its principal uses are for measuring high voltage and for taking measurements where current drawn by a current-sensitive meter would give erroneous results.

The applications of electrostatic meters are quite limited. You've no doubt noted that all of these meters have features in common. Most consist of a stationary element, a moving element, a controlling element (torque spring or springs), a moving-element mounting, a pointer, a scale, and a case with terminals for electrical connections. On an electrical measuring meter, the *stationary element* may be a permanent magnet, a coil, or a plate. Its function is to furnish a magnetic or an electric field to react with the field around the moving element. The *moving element* is the part that rotates when it's energized, moving the affixed pointer across a calibrated scale. The *controlling element* is usually one or more springs whose counter force increases as the moving element turns and brings the pointer to rest at some position on the scale. The controlling element in moving-coil mechanisms is made of nonmagnetic metal, which serves as a conductor to the moving coil. The *moving-element mounting* has pivot points, fitted into bearings, so that it can rotate with little friction. In some mountings, the pivot points are reversed and the bearings are inside the moving-coil assembly. The bearings are either highly polished jewels such as sapphires or synthetic jewels, or hard glass. Each bearing is round with a conical depression into which a pivot point fits and is set in threaded nuts to adjust for end play. The radius of the depression is greater than the radius of the pivot point, so that the area of contact surface is limited. This arrangement gives us a bearing that probably has the lowest contact friction value of any known type when it is operated dry.

Damping refers to the way we bring the pointer of an electrical indicating instrument to rest quickly after it has been set in motion. Damping may be electromagnetic, mechanical (air or liquid damping), or a combination of the two. To dampen DC meters electromagnetically, the moving coil is wound on a light aluminum frame so that eddy currents, caused by motion of this coil in the permanent-magnetic field, are set up in the frame. The magnetic field produced by the eddy currents interacts with that of the permanent magnet to oppose the motion of the coil. AC meters use the same principle, but the construction is slightly different. An aluminum disk mounted on the moving element's shaft moves between the poles of a small permanent magnet. Air damping is often used, especially in the dynamometer and the moving-vane types. A light vane attached to the pointer shaft is inclosed in an air chamber (fig. 1-23). When it's forced to move, the vane compresses air in front of it because of the small clearance between the walls of the chamber and the vanes. This slows the vane's motion, damping the meter. In liquid damping, all or part of the meter movement is immersed in an oil chamber to damp the movement.

The type of scale marked on the dial of the meter depends on the meter's construction. Three scales commonly found on meter dials are the uniform (or linear), the square-law, and the logarithmic (fig. 1-24). Most moving-coil meters used for DC measurements have a linear scale (equal spaces between numbers) like the one shown in figure 1-24,A. The amount of deflection is directly proportional to the amount of current through the coil. Thus, when all the rated current flows through the meter, the pointer deflection is full scale; when the current is half, the deflection is half-scale, etc.

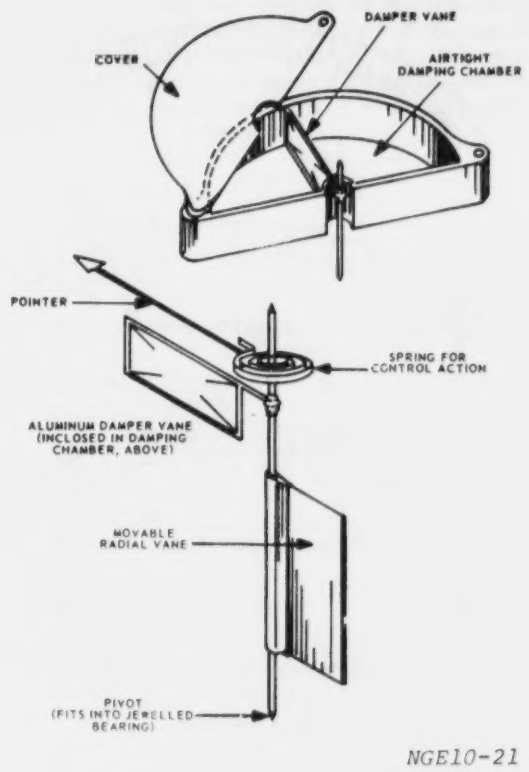


Figure 1-23. Mechanical dampers.

Some moving-iron movements cause the pointer to indicate according to the square-law scale rather than in direct proportion to the amount of current flow. For example, if the current is doubled, the magnetic field around each vane is twice as strong. Since each vane repels twice as much, the combined repulsion of the two vanes is four times as great. Therefore, by doubling the current, we get four times the deflection, and by tripling it, we get nine times the deflection, etc. Deflection is therefore *square-law*, and the scale is *nonlinear*, with the numbers on the low end crowded together and the numbers on the high end spread farther apart. In a true square-law scale, any point that represents twice the value of a point lower on the scale also represents four times the deflection. For example, figure 1-24,B, shows full-scale deflection as 10 and quarter-scale deflection as 5. The logarithmic scale (fig. 1-24,C) is used on meters that measure power or volume levels.

Accuracy and sensitivity. A meter's accuracy and sensitivity can't be altered without changing the meter's construction. These characteristics are determined by the manufacturer, but you should have a general idea of your meters' accuracy and sensitivity. Moving-coil meters made for laboratory use have a high accuracy (0.1 percent). Some semiprecision meters have an accuracy of 0.5 to 1.0 percent, but most meters in general use have an accuracy of

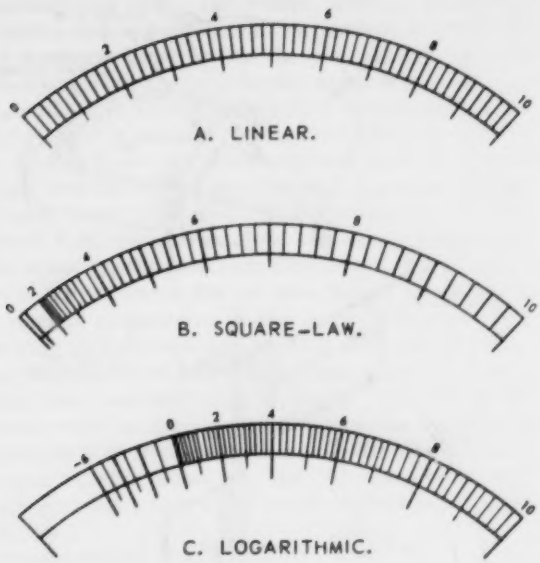


Figure 1-24. Scales.

2.0 percent for full-scale readings on any range. The sensitivity of a meter movement is usually expressed as the "amount of current required to give full-scale deflection." Sensitivity may also express the number of millivolts across the meter when full-scale current flows through it. For example, the sensitivity of a meter movement may be specified as 50 mV, 0-1 mA. With this 50-mV full-scale deflection, we can compute the internal resistance by dividing this voltage by the full scale current. Thus, R_m = 50 mV/1mA, or 50 ohms, where R_m is the internal resistance of the meter. On the other hand, if you know R_m instead of the full-scale voltage, you can find this voltage by multiplying R_m by the full-scale current.

Every meter coil has a definite amount of DC internal resistance that depends on the number of turns and on the size of the wire. When we place more windings on the coil, we need less current to create a magnetic field strong enough to deflect the coil full scale. Sensitivities vary from 5 microamperes to about 50 milliamperes. Naturally, the less current we need for full-scale deflection, the greater the sensitivity.

Exercises (205):

1. What are three types of meter movements?
2. Which type uses an electromagnet?
3. Why are electrothermal meters relatively sluggish?
4. What actuates an electrostatic meter movement?
5. List six parts common to most meter movements.

206. Identify types of ammeters by their uses.

Ammeters. Although a *current-sensitive* movement is essentially an ammeter, it can't measure the range of currents found in electronic circuits. If the values exceed the movement's rating, the overload may seriously damage the meter. One way to extend an ammeter's range and prevent damage is to connect a resistor in parallel with the meter movement. The parallel resistor (shunt) bypasses part of the current, reducing the current through the movement. With shunts, we can extend the range to whatever value we need. Many ammeters are designed to measure current (DC or AC) in several ranges.

DC ammeters. Recall that all current-sensitive movements are actuated by DC. Thus, we need only find the value of a shunt to have a DC ammeter for a desired range. Look at figure 1-25 and note that the voltage, V, across the movement and shunt is the same. It follows, then, that:

$$IsRs = ImRm$$

$$RS = \frac{ImRm}{Is}$$

As you can see in figure 1-25, Rs is the shunt resistance, Rm is the meter movement resistance, Is is the shunt current, and Im is the meter movement current for full-scale deflection. Note also that the maximum current to be measured is I = Is + Im, so Is = I − IM. Substituting for Is in this formula, we have

$$RS = \frac{ImRm}{I - Im}$$

Now we can easily compute Rs, because Im, Rm, and I (the upper limit of the range) are values that we know. Suppose, for example, that we have a movement with a sensitivity, Im, of 1 mA and a resistance, Rm, of 60 ohms, and we want to make a 5-mA ammeter. Applying the formula, we calculate the value of the shunt, Rs:

$$Rs = \frac{1 \times 60}{5 - 1} \text{ ohms} = 15 \text{ ohms}$$

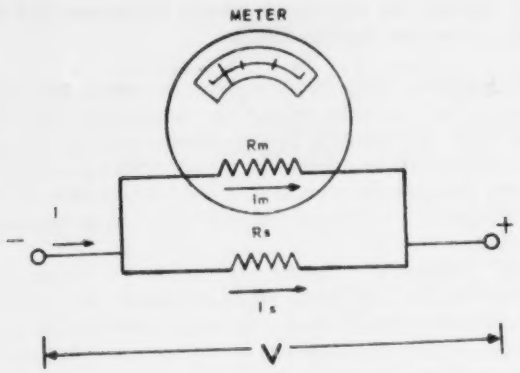


Figure 1–25. Basic DC ammeter.

Since electronic currents are normally small, most ammeters have shunts inclosed in the meter case. These shunts can be made of copper, silver, or any low-resistance conductor. When the current to be measured is high, the shunt is usually outside the meter case to prevent injury to the movement from heat generated by the shunt.

Multirange ammeter. A multirange ammeter (fig. 1-26) can have either a switching arrangement or separate pin jacks to change from one range to another. Most commercial milliammeters use a tapped resistor called a *universal, or ring, shunt*. Some or all of the resistance is added in parallel with the resistance of the meter movement and some or none of the resistance is in series, depending on the selected range. Ring shunts have an advantage over separate shunts, because when part of the total resistance is in series with the meter movement, the parallel resistors don't have to be as low in value.

Figure 1-26,A, illustrates that on the lowest range, 15 mA, all of the resistors are in shunt with the meter movement. Since the meter's resistance is just half that of the shunt, half as much current goes through the shunt (5 milliamperes) as through the movement (10 milliamperes) to take care of the full-scale 15 mA through the meter. In figure 1-26,B, there are two series resistors, with a total of 18 ohms, in shunt with the 30-ohm movement and the resistor of 42 ohms. For this condition, the current through the shunt path is four times that through the movement, so full-scale deflection occurs for 50 mA—40 mA through the shunt and 10 mA through the movement. Study figure 1-26,C, and note that the ratio of Is to Im is 9:1, which gives a full-scale indication for 100 mA.

AC ammeters. Except for the permanent-magnet moving-coil movement, either DC or AC actuates a meter movement so the same scale can indicate either DC or the effective (RMS) value of AC. If we have to use the Weston movement (which responds only to DC), we'll need a rectifying circuit and a separate AC scale.

A half-wave or full-wave rectifier can be connected to the Weston meter, as shown in figure 1-27,A, and B, respectively. For a sine-wave input, the movement indicates the average current, which is 0.45 of the effective (RMS) value for the half-wave rectifier and 0.9 of the

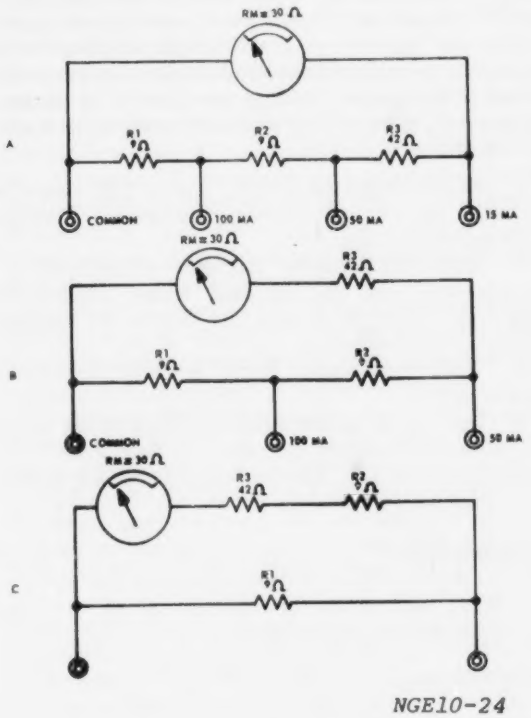


Figure 1–26. Multirange DC ammeter.

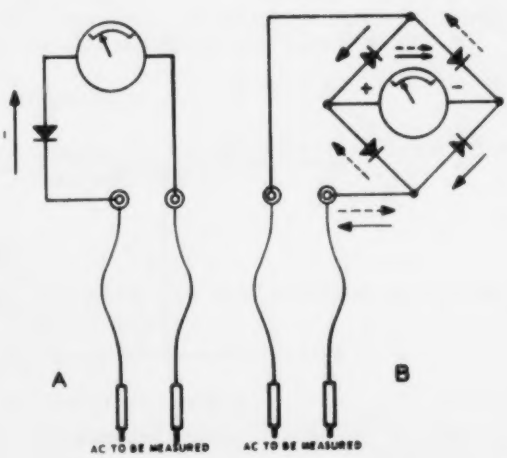


Figure 1–27. AC ammeter circuits.

effective value for the bridge rectifier. Since the scale is generally calibrated to read in RMS values of a sine wave, waveforms other than sine waves give erroneous readings. When a capacitor and large resistor are added in a rectifier circuit (fig. 1-28), the output is roughly equal to the peak value of the applied AC, and the meter indicates peak values. An advantage of the shunt rectifier is that the capacitor blocks any DC component applied by the voltage source, so we read AC only. Both of the rectifiers illustrated cause the meter to indicate peak *positive* values. To get peak *negative* values, we must reverse the diodes in each circuit. Here are a few other noteworthy facts about AC ammeters:

a. We can extend the ammeter's range with shunts, but we often use stepdown current transformers to measure large currents.

b. Since the inductive reactance of the coil in a dynamometer and an iron-vane meter changes with frequency, these movements are limited to measuring relatively low frequencies.

c. The thermocouple meter is most suitable for measuring RF.

d. True AC ammmeters indicate RMS values for any waveform. (Remember that when you use a rectifier in conjunction with a DC ammeter, its RMS reading is correct only for sinusoidal waveforms.)

Exercises (206):

1. What type circuit do we add to use a Weston movement as an ammeter?

2. Which two AC ammeters are limited to measuring relatively low frequencies?

207. Specify the differences among voltmeters and the ways to increase their usefulness.

Voltmeters. Since the electrostatic movement finds very limited use in electronics, the movements used for voltmeters are virtually always current-sensitive. To use such movements in a voltmeter, we add a high resistance in series, reducing the current to a level the movement can handle safely, even though the meter is placed across a high voltage.

DC voltmeters. Figure 1-29 shows a simple DC voltmeter. To find what series resistance you need to measure any given voltage, you must know the full-scale current, the internal resistance of the meter, and the desired voltage range. You needn't deduct the internal resistance if it's small compared to the series resistance. If we place a 10,000-ohm resistance in series with the meter movement in a circuit with 10 volts applied, 1 mA flows through the circuit and the needle swings to maximum. With this amount of resistance, the voltmeter can measure 10 volts without damage. This series resistance is known as a multiplier because it extends the voltage range of the meter. The scale then can be calibrated in volts, with 10 volts representing full-scale deflection. If we put the meter across 5 volts, only 0.5 mA flows through the movement, and the meter reads half the full-scale value.

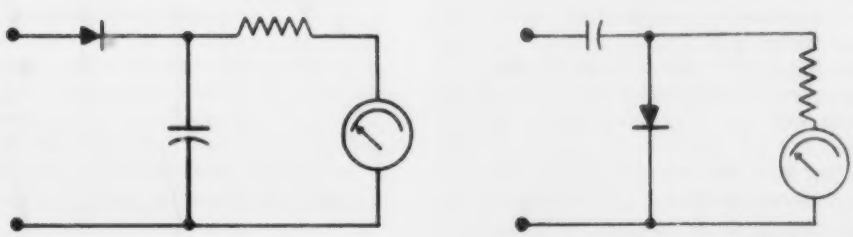
The second way to calculate a multiplying resistor is based on *ohms per volt*:

$$\text{Ohms} - \text{per} - \text{volt sensitivity} = \frac{1}{\text{current sensitivity}}$$

Let's see what series resistance we need in a meter movement with a sensitivity of 1 mA:

$$\frac{1}{0.001a} = 1000\ \frac{\text{ohms}}{\text{volt}}$$

Thus, we can call a 1-mA movement a 1000-ohms-per-volt movement. Meter movement sensitivity is commonly expressed in ohms per volt because it is easier to find out what multiplier resistance we need for a given range. When you know the ohms-per-volt rating, you multiply it by the



A. SERIES RECTIFIER (PEAK READING)

B. SHUNT RECTIFIER (PEAK READING)

NGE10-26

Figure 1-28. Peak reading, AC ammeter circuits.

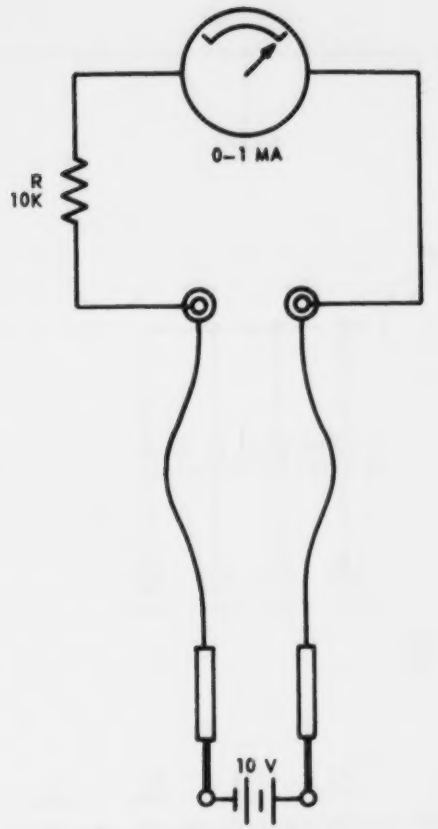


Figure 1–29. Basic DC voltmeter.

range in volts to find the multiplier resistance. A voltmeter that has several ranges has either a switching arrangement (fig.1-30,A and C) or separate pin jacks for each range (fig.1-30,B and D). Figure 1-30,A, is the schematic for a four-range switch selector voltmeter with separate multipliers for each range. In figure 1-30,B, each multiplier is connected to a separate pin jack instead of a switch. The negative lead is placed in the negative pin jack, and the other lead is put in the positive pin jack of the voltage range desired. The voltmeters in figure 1-30,C, and D have five ranges and use 0.5-mA movements. Their ohms-per-volt sensitivity is 2000 ohms, so the 10-volt range needs a 20k-ohm multiplier, and the 100-volt range needs a 200k-ohm multiplier. Since R2 is in series with R1 (20k), its value should be 180k ohms. We can find the multipliers for the other ranges the same way, with R3, R4, and R5 providing the additional resistance for each higher range. Resistors used as multipliers are either carbon or wirewound. The more expensive meters use precision wire-wound resistors with a tolerance of 0.1 percent. We use the (cheaper) carbon resistor where we don't need a precise reading or as an emergency, temporary replacement to keep needed test equipment in service.

AC voltmeters. If the movement used in a voltmeter is actuated by AC and DC, the scale reads the RMS value of any AC voltage within its range. When a movement is actuated only by DC (e.g., the Weston type), we must have a rectifier circuit and separate scales for AC. What we said earlier about AC ammeters with rectifiers pertains also to AC voltmeters with rectifiers. The RMS scales on these voltmeters are true only for sine-wave voltages. Figure 1-31 illustrates how a half-wave rectifying AC voltmeter can be arranged to prevent meter inefficiency caused by reverse current in a solid-state rectifier, particularly a metallic-oxide type. With the movement shunted by diode D2, practically no reverse voltage appears across diode D1. If we omit diode D2, the reverse current through D1 reduces the average rectifier current and the deflection of the meter. This is true also for AC ammeters, but the effect of reverse current is more objectionable in AC voltmeters because the resistors are in series with the movement.

Rectifiers are so widely used with DC meters that another matter should be brought to your attention. A rectifier's forward resistance varies with current in the low-current range, making the meter's calibration somewhat nonlinear. To overcome this difficulty, we can place a shunted movement in series with the rectifier. Since this rectifier passes more current, its operation is more linear. For example, if the movement has a sensitivity of 200 μA and the shunt has one-fourth the resistance of the meter movement, four times as much current flows through the shunt. At full deflection, 800 μA flows through the shunt, 200 μA through the meter, and 1 mA through the rectifier. Thus, the rectifier current is increased by a factor of 5. Even at low meter readings, a substantial amount of current flows through the rectifier when a shunt is used and the change of rectifier resistance is small. With a proper choice of shunt values, the scale is virtually linear. Figure 1-32 shows a typical commercial circuit of a copper-oxide rectifier with a 1000-ohms-per-volt sensitivity. This circuit includes both series and shunt variable resistors to adjust for rectifier variation and rectifier component replacements. To calibrate the meter, we can apply a known AC voltage and vary the resistors until the scale reads correctly.

Exercises (207):

1. What do we call the series resistor that extends a voltmeter's range?

2. Why do we use a meter movement shunt in a rectifier AC voltmeter?

3. What determines the direction of the lines of flux about a wire?

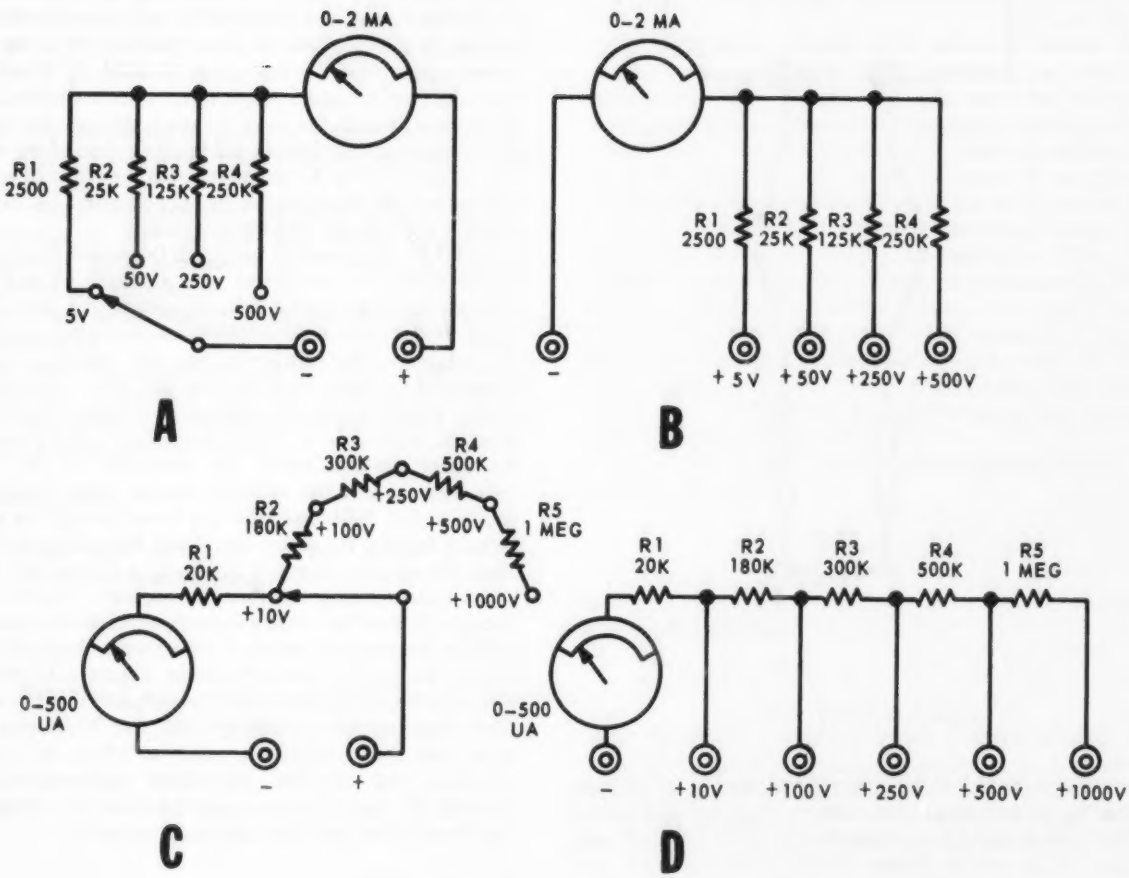


Figure 1–30. Multirange circuits for DC voltmeters.

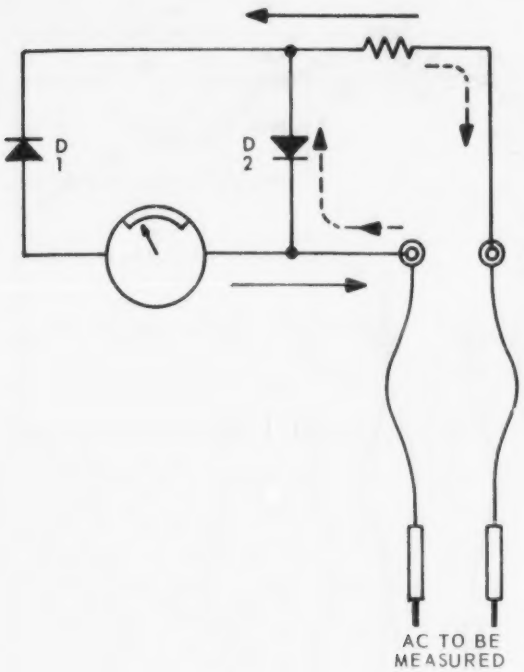


Figure 1–31. Half-wave rectifying AC voltmeter.

208. State the functions of ohmmeter circuit components.

Ohmmeters. Most ohmmeters can cover a number of ranges from low to high resistance by connecting various values of current-limiting resistors in the ohmmeter circuit. We can select the range by using individual input terminals or by a selector switch. As with other meters, some ohmmeter circuits are in series; others are shunt.

Series ohmmeters. A basic ohmmeter consists of a current-sensitive movement (usually a Weston meter), a source of low-voltage DC, and some form of current-limiting resistor. Figure 1-33 shows the basic series ohmmeter circuit. The two leads, P1 and P2, represent the test prods that are connected across the resistance to be measured, RX. R1 limits the flow of current to prevent meter damage. Variable resistor R2 is controlled by the front panel knob marked OHMS ZERO ADJ (not shown in fig. 1-33). You adjust R2 to allow for full deflection—that is, for 1-mA flow with the test prods shorted together. In a series meter, full-scale deflection indicates the lowest resistance and the opposite end indicates the highest, the values increasing progressively from *right to left*. This circuit can't measure accurately the low resistance of coils, chokes, and transformer windings, which are often 5 ohms or less. We can't consider low values (within the right quarter of the scale) very accurate. In the circuit of figure 1-33, a resistance of 5000 ohms deflects the pointer over nine-tenths of the scale, so one-tenth of the scale represents 500 ohms. One-tenth of this division represents 50 ohms, and one-tenth of that (1/1000th of the scale) represents 5 ohms. We can't read the high-resistance part of the scale accurately, because the values get crowded at that end. The midscale area is the most accurate part of the scale.

Shunt ohmmeters. Look at figure 1-34, and let's see how we can measure low values of resistance. The unknown resistor, RX, is shunted across the meter; thus, some of the current in the circuit takes the path through RX. With test prods P1 and P2 open, and R2 adjusted for full-scale deflection, a current of 1 mA flows through the circuit. In this scale, the indicated resistance is opposite to that of the series type, for the values progress *from left to right*. The usable scale of the shunt-type meter circuit in figure 1-34 ranges from about 5 to 400 ohms. Resistances falling above or below these amounts are hard to measure with any degree of accuracy because they fall at the ends of the scale. If you have to be more precise for low values of RX, you must extend the meter scale by adding to the unit shunts that have the required resistance values. You then select the range by connecting the proper shunt across the meter with individual terminal jacks or by a multiposition rotary switch. With such an arrangement, we can measure values as low as a fraction of an ohm with considerable accuracy because a resistance range that has very low limits can be spread over the entire meter scale.

Multirange meters. A multirange ohmmeter circuit has one high-resistance and two low-resistance ranges (fig. 1-35). It is basically a series ohmmeter because the unknown resistor is in series with the meter. Shunts are placed across the meter to give more distinct readings in the lower ranges. With the range switch in position 3, high values of resistance can be measured across test prods P1 and P2. For a low-resistance check, set the range switch to position 1, placing R1 in parallel with the meter. Since this change alters the series resistance of the circuit, adjust R3 for zero ohms. For a still lower range, set the switch to position 2 and readjust R3.

A practical way to get the various range readings is to calibrate the meter in terms of the lowest scale, then use multiplying factors to get the measured values for the other ranges. The multiplying factors for the series ohmmeter are usually in multiples of 10 and are indicated on the panel as R × 1, R × 10, or R × 100. You multiply the scale reading by the proper factor to get the value of the resistance. In the circuit of a commercial ohmmeter that measures resistance from 0.2 ohm through 20 megohms (fig. 1-36), the variation is covered in three ranges: 0 to 2000 ohms on the low range; 0 to 200,000 ohms on the second range, and 0 to 20 megohms on the high range. The first two are powered by a 1.5-volt battery, and the extension to the high range is made by using 7.5 volts. As we said, the meter scale is calibrated in terms of the lowest range and you use a multiplying factor to find resistance values on the other two ranges. Since the multirange ohmmeter is a series type, you

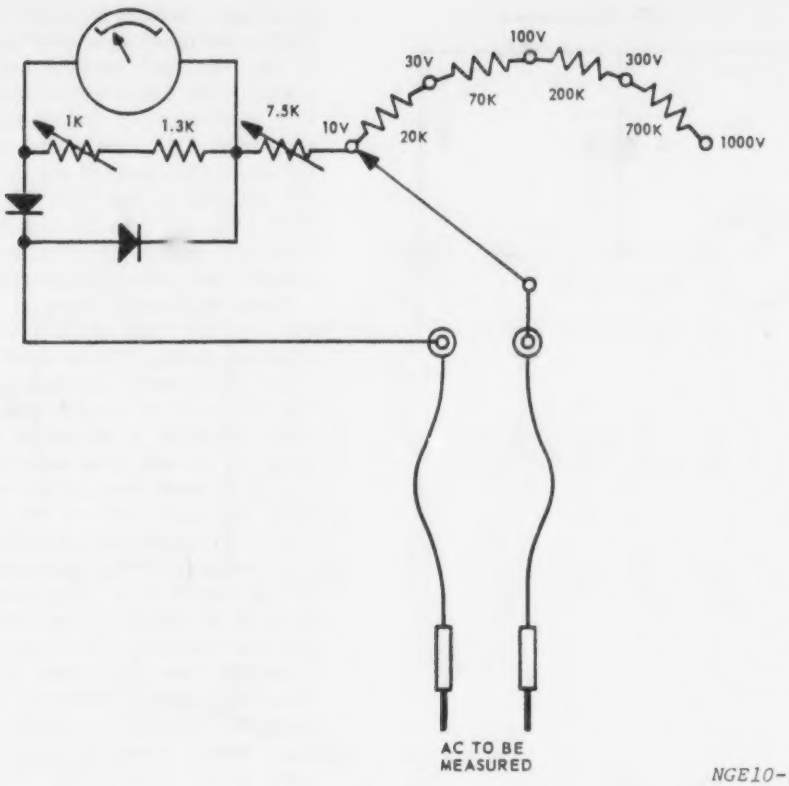


Figure 1–32. Typical commercial AC voltmeter.

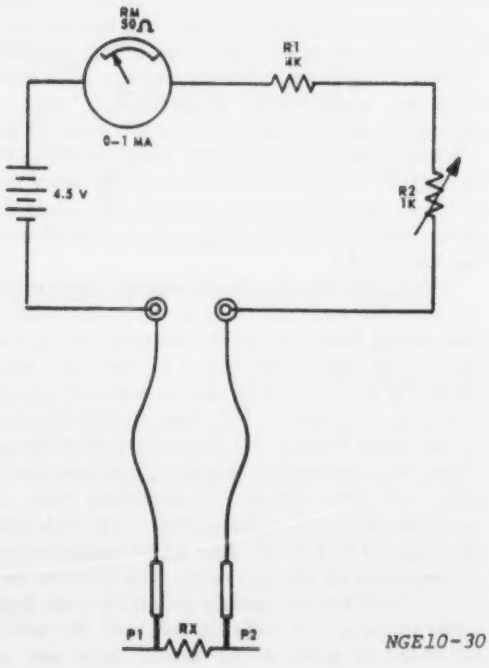


Figure 1–33. Series-type ohmeter.

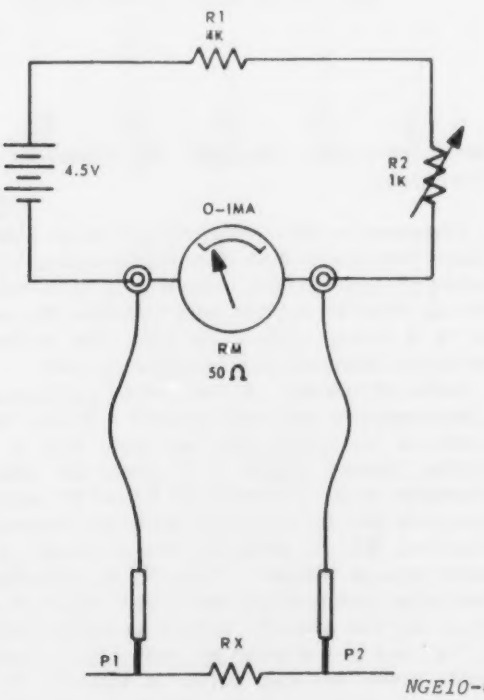


Figure 1–34. Shunt-type ohmeter.

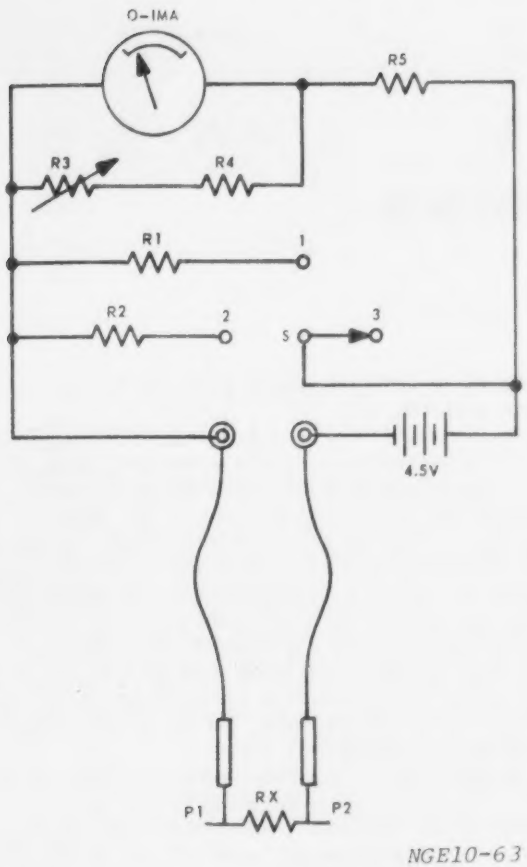


Figure 1-35. Multirange ohmeter.

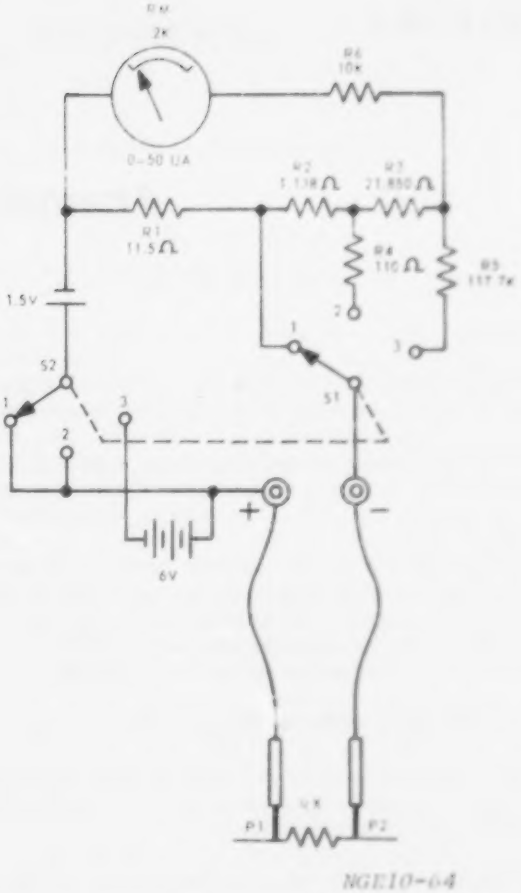


Figure 1-36. Typical ohmeter.

read it from right to left, with the highest resistance for each range at the extreme left of the scale.

Exercises (208):

1. Why are meter shunts used in ohmmeters?

2. Why are multirange ohmmeters basically series-type ohmmeters?

3. A series ohmmeter reads most accurately in what part of its scale? Why?

CHAPTER 2

Alternating Current

OUR PURPOSE in this chapter is to discuss the basic concepts used in analyzing AC circuits. You should realize that AC circuits encompass a very broad subject area, both from the standpoint of operating frequency and circuit configuration. We can't expect to cover all of the concepts of mathematics and electrical phenomena you need for a complete analysis of all the AC circuits in a modern communications system, but there are a number of circuits and networks you can analyze by the same methods you used for DC circuits. This chapter reviews the essential principles of capacitance, inductance, and resistance in AC circuits and briefly discusses AC and DC generators.

2-1. Principles of Alternating Current

The current flow we discussed in Chapter 1 is direct current (DC). Now let's look at AC, the current that reverses its direction periodically.

209. Define basic AC terms and find the peak, effective, and average voltage in given problems.

Waveforms. The most common waveform is the sine wave (fig. 2-1). Notice that the sine wave increases to a maximum amplitude in one direction and then decreases to zero. It then increases to a maximum amplitude in the opposite direction and again decreases to zero. The sine wave of voltage or current is continuously changing in amplitude and periodically reversing direction. Note that the sine wave line divides into two equal parts: one above the line and the other below it. The part above the line is the positive alternation, and the part below the line is the negative alternation. The wave reaches its maximum swing from zero at 90° and 270°. Each of these points is called the peak of the sine wave. When we refer to the peak amplitude of a sine wave, we mean the maximum swing, or the height of one of the alternations at its peak. These terms apply to either current or voltage, and it is important for you to remember this because you will be using them throughout your career. The sine wave in figure 2-1 represents the difference in value between the positive and negative peaks of voltage. Of course, this is twice the peak value. Why is the term "peak-to-peak" so important? Suppose you want to find the amplitude (voltage) of a sine wave. By using the peak-to-peak value and dividing it by 2, you can get an accurate peak amplitude. If each graphic unit on a scope represents 8 volts and the peak-to-peak wave measures 10 units, the peak-to-peak voltage is 80 volts. The peak value, then, is 40 volts.

A more useful value in working with AC is the *effective* value, or the amount that produces the same heating effect as an equal amount of DC. Since the heating effect of a quantity of current is proportional to the square of the current, you can calculate the effective value by squaring the instantaneous values of all points on the sine wave, taking the average of these values, and extracting the square root. The effective value is the root of the mean (average) square of these values, known as the *root-mean-square*, or rms value. When we say an AC voltage is 110 volts, we mean that it has an effective, or rms, value of 110 volts. Unless we're told otherwise, the stated AC voltage or current means the effective value.

Suppose you have a sine wave with a peak amplitude of 1 volt. The square root of the average of the squares of the values of this sine wave is .707. This means that a sine wave of voltage whose peak value is 1 volt will have the same heating effect as .707 volts of DC. To find the effective value of AC, multiply .707 times the peak value. The reciprocal of .707 is 1.414. Therefore, if you know the effective value, you can find the peak voltage by multiplying the effective value by 1.414.

Another value in a sine wave that is important to know is the *average* value. This is the average of the instantaneous values of all points in a single alternation. (The average of a complete sine wave is zero.) The average height of a single alternation (positive or negative) is .636 times the peak value. The relationship among the average, effective, and peak values can be shown mathematically in the formula:

$$E_{av} = .636E_{pk} = .9E_{eff}$$

As you can see, average voltage is .636 of the peak, or maximum, voltage and .9 of the effective voltage. The reciprocal of .636 is 1.11, so the effective voltage is 1.11 times the average voltage.

Frequency Terms. As we said before, AC is reversing direction periodically. Two alternations, one positive and one negative, make one full cycle. The positive and negative alternations are half-cycles. The number of cycles in a given time is called the *frequency*. The universally used unit of frequency is the *hertz* (Hz). In electronics, 60 hertz is a relatively low frequency. We often talk of frequencies in the thousands and millions. For frequencies in the thousands, we use the term *kilohertz* (kHz); for frequencies

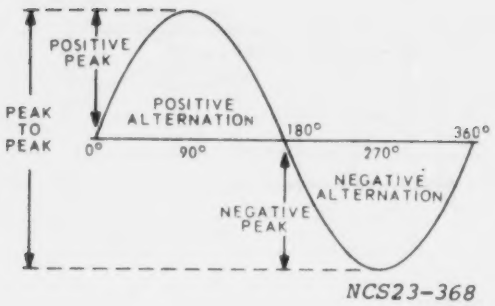


Figure 2–1. An AC sine wave.

in the millions, we use the term *megahertz* (MHz). If the time of one cycle is one thousandth of a second, the frequency is 1 kilohertz; if it's one millionth of a second, the frequency is 1 megahertz (f = 1/T). Figure 2-2 shows the universal frequency spectrum.

We said that current or voltage may occur as sine waves. Since voltage is used to produce current, let's compare the sine waves in a different way. Figure 2-3 shows three sine waves. The top wave represents voltage; the other two represent the current produced by that voltage. Note that the voltage sine wave A and the current sine wave B move together. Since the two sine waves go through all phases of the cycle together, they are said to be in-phase. The term "in-phase" is not limited to just the voltage and the current produced by the voltage. You can also speak of two alternating voltages or two alternating currents that rise and fall together as being in phase. Current is in-phase with the voltage only in circuits that are purely resistive. There are electrical components that affect the voltage and the current phase relationships in AC circuits. When one of these components is included in a circuit, current and voltage are out of phase. There's an out-of-phase relationship any time the waves don't move simultaneously.

Comparing sine wave A and sine wave C, you can see that the current sine wave is maximum negative when the voltage sine wave is zero (at the start of its positive half-cycle). In describing this relationship, we say that the current lags the voltage by 90°. If the current sine wave comes before that of the voltage, then the current leads the voltage.

Exercises (209):

1. Find the peak, effective, and average voltage from a 200 peak-to-peak voltage.

2. Find the peak and average voltages from a 110 effective voltage.

3. Define kilohertz and megahertz.

4. What's an out-of-phase relationship?

2-2. Alternating-Current Generators

In this section, we'll cover two alternating-current generators. First, we'll review the three requirements for induction and then discuss how AC is developed by moving a conductor through a magnetic field.

210. List the requirements for induction, state how AC current is developed, and name the components of an AC generator.

Induction and Current Flow. There are three requirements for induction. You must have a conductor (a coil of wire), a magnetic field (a permanent magnet), and motion between the magnetic field and the conductor so that the conductor cuts across the magnetic lines of force. Figure 2-4,A, shows a conductor moving downward through a stationary magnetic field whose lines of force go from left to right. Notice we now have the three requirements for induction. As the conductor moves down through the field, the field tends to circle the inductor counterclockwise. This induces a voltage in the conductor, causing a current to flow. The left-hand rule shown in the figure may help you understand the principle. Notice the position of the thumb, first finger, and middle finger. You can see that the hand is drawn to fit the conditions shown in detail B in the figure. Detail A shows that the current in the conductor is flowing away from you (into the page) and is represented by a plus sign in the center of the conductor.

Now see what happens when we move the conductor through the field in the opposite direction, as shown in detail B. You can see that lines of force circle the conductor clockwise, so the current is flowing toward you (out of the page). This is shown by the dot in the center of the conductor. From this illustration, you can see that a change in the direction of relative motion produces a change in the direction of current flow in the conductor.

Detail C shows the conductor moving parallel to the lines of force. Notice that the lines of force don't circle the conductor as they did when the conductor was moved up or down, so no voltage is induced. Now let's see what happens when we rotate a loop of wire in a magnetic field. Figure 2-5 shows a cross-section of the two ends of the loop, one at A and the other at B. At the instant the loop is in position A–B (shown in fig. 2-5,A), the conductor is moving parallel to the lines of force and no current is induced in the loop.

As the loop is rotated from A–B to A2–B2, it cuts across lines of force until it cuts a maximum number at 90° (position A2–B2). If we look at the conductor at A2, we see that the current is going in (away from us) as indicated by the plus symbol. At the same time, the current is coming

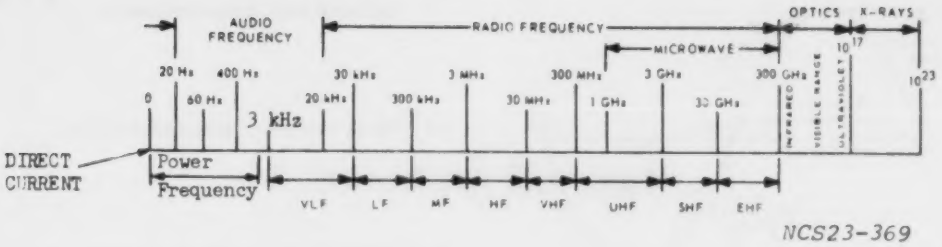


Figure 2–2. Frequency spectrum.

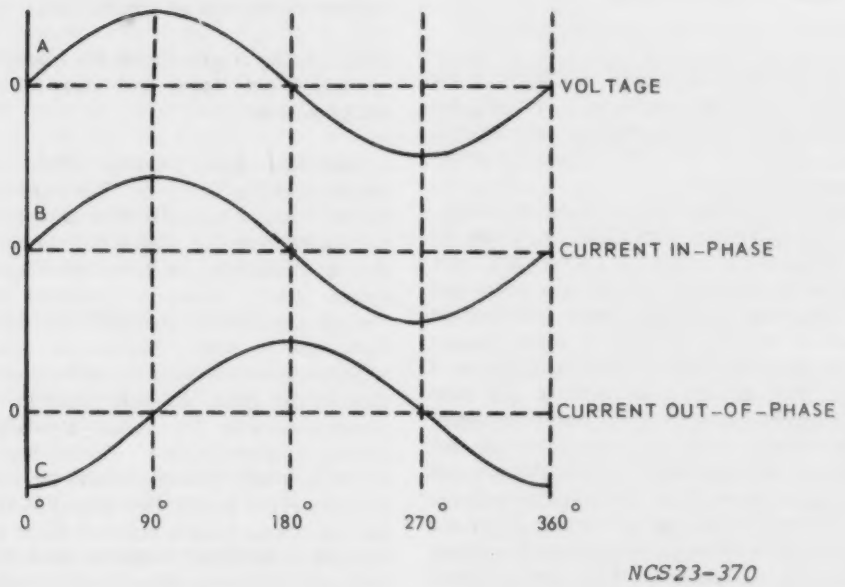


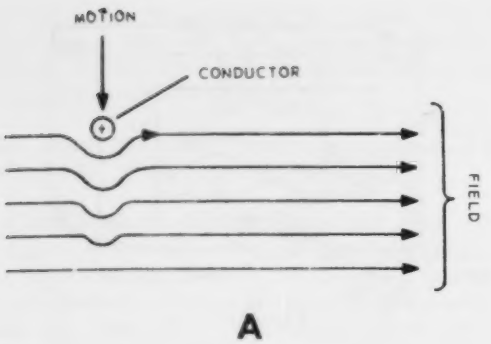
Figure 2–3. Phase relationship.

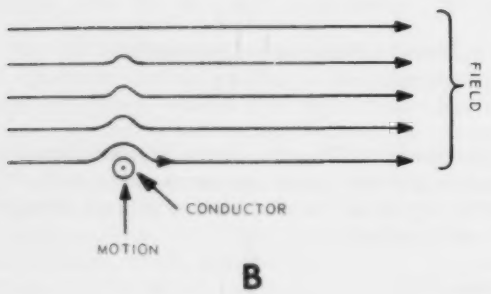
out (toward us) in B2 as indicated by the dot. In other words, the current flow is from A2 to B2.

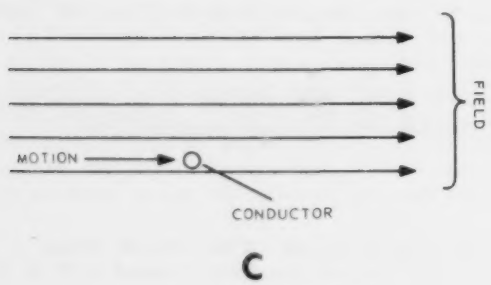
Now assume that the loop is rotated further to position A3–B3, as shown in figure 2-5,B. The amount of induced current decreases until it reaches zero at position A3–B3. At any position between A2 and A3, the current is going in. As end B moves from position A–B to A3–B3, the current induced in the loop varies from zero to maximum and back to zero, and the current flow is from A to B. As the loop continues to rotate from A3–B3 to A4–B4 (fig. 2-5,C), you can see that the loop again cuts lines of force, inducing a voltage in the loop. However, the A end of the loop is now cutting the lines of force in the opposite direction. Now the plus symbol shows that the current is coming out at A. We find that the bend is also cutting the field in the opposite direction. The dot symbol shows that the current is now going in at B. In other words, the current flow is from B to A in the loop. When the loop reaches position A4–B4, the current flow is at maximum. As the loop rotates back to the starting position, the current flow again goes to zero. One revolution of the loop fits our definition of AC: the amplitude is continuously changing, and the polarity is periodically reversing.

Factors Determining Current Magnitude. Now let's see how changing one of the three induction requirements affects the induced voltage. Basically, the magnitude of the induced voltage depends on the number of magnetic lines of force cut by the conductor in a given period of time. This can be varied in three ways. First let's look at figure 2-6. Notice that in detail A, the magnetic field has considerably fewer lines of force than in detail B. Thus, at the same speed of rotation, the conductor in detail B is cutting more lines of force than the one in detail A. This produces a higher induced voltage in the conductor in detail B and, therefore, a higher current flow. You can see that a stronger magnetic field induces a higher voltage in the conductor.

What happens when we vary the relative motion between the conductor and the magnetic field? Let's look at figure







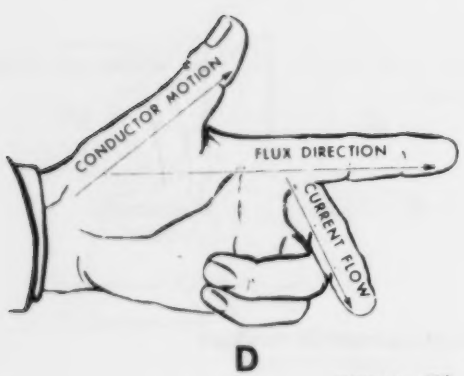


Figure 2–4. Current motion relationship.

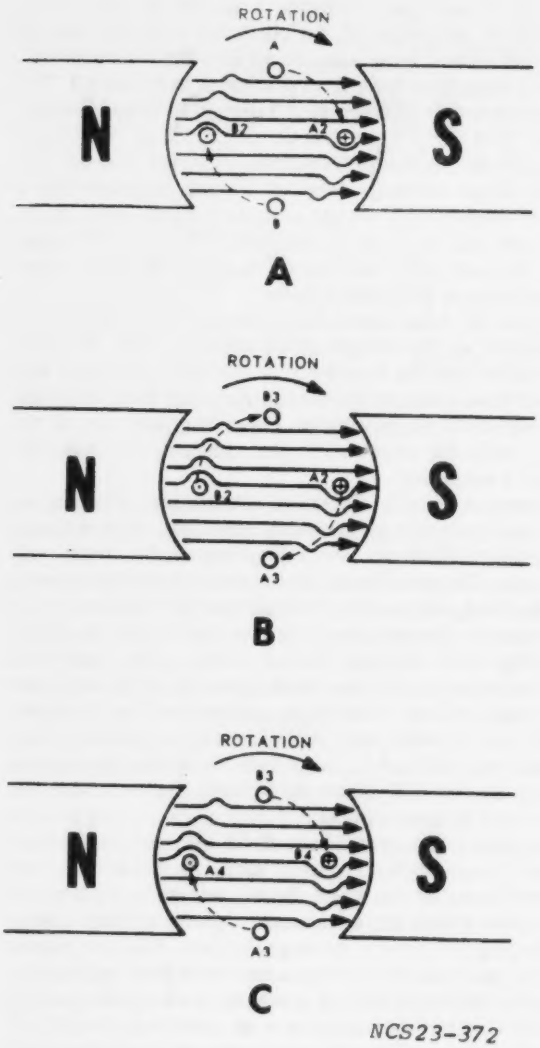


Figure 2–5. Effects of a rotating magnetic field.

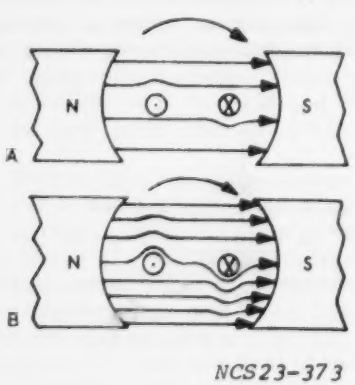


Figure 2–6. Rotating conductor.

2-7. If it takes the conductor 1 second to move from position A to position B, the conductor cuts five lines of force per second. Now, suppose we slow the conductor so it takes 2 seconds to move from position A to position B. The conductor is now cutting only 2.5 lines of force per second.

The third factor that varies the magnitude of the induced voltage is the number of conductors. If we use a single-loop conductor as we have done so far, the generator has a certain output; but if we use a conductor with more loops, each loop will have nearly the same current as the single loop. Because these currents are in series, the total output will increase as each loop is added.

Again, the three factors that determine the magnitude of the current are the strength of the magnetic field, the speed of rotation, and the number of conductors. Increasing any one of these (without decreasing the other two) increases the magnitude of the current. Decreasing any one of the three, while the other two remain constant, decreases the current's magnitude.

Components of a Basic AC Generator. Keeping in mind this basic idea of how AC is developed, look at figure 2-8, which illustrates the components of a basic AC generator. The pole pieces are the two ends of the magnet, and the field coil provides the magnetic lines of force at the pole pieces. The armature, the part that rotates, includes slip rings and windings around a core. (The source of mechanical power to rotate the armature is not shown.) The slip rings are two metal rings mounted on the armature shaft, one for each end of the rotating conductor. The brushes are stationary contacts that ride on the slip rings to pick up the induced current and voltage. Let's examine the function of each component.

The pole pieces provide a path for the magnetic lines of force. They also have curved faces to spread the flux uniformly across the space for the armature. Sometimes these pole pieces are permanent magnets; in other cases, electromagnets provide the magnetic field. The pole pieces and the generator frame form a low-reluctance path for the magnetic field. The rotating conductor is the winding on the armature core. The armature core provides a means of mounting and rotating the conductor, as well as a low-reluctance path between the pole pieces. As the conductor rotates in the magnetic field, it cuts the magnetic lines of force, inducing a voltage in the rotating conductor. The slip rings rotate with the armature, while the brushes remain stationary and slide over the surface of the slip rings, conducting the induced current from the rotating conductor

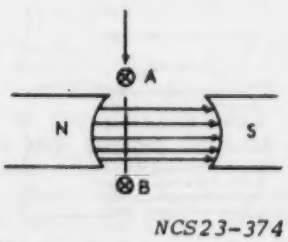


Figure 2-7. Varying rotating conductor's speed.

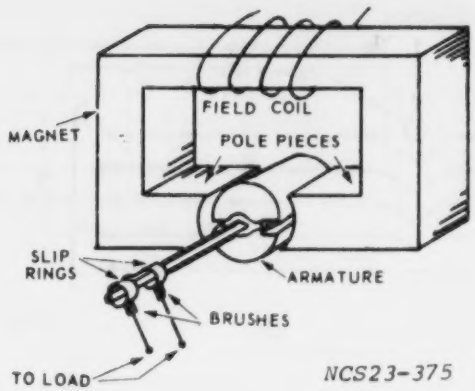


Figure 2-8. Basic AC generator components.

to an external circuit. The external circuit and load provide a path for the induced current so it can do useful work. The load can be any device that conducts current, such as lamps, motors, and transformers.

Exercises (210):

1. List the three requirements for induction.

2. How is current flow affected if the conductor is moving horizontally through a magnetic field?

3. What is the magnitude of the induced voltage in a conductor when the conductor is moved at 90° to the magnetic lines of force?

4. What three factors vary the amount of induced voltage?

5. Name the components of an AC generator.

2-3. Direct-Current Generators

We just reviewed the generation of AC; now let's look at the components of a basic DC generator, the way DC is generated, the different outputs of a DC generator, and the characteristics of three types of DC generators. Although

we won't cover DC motors in this volume, they are like generators in that each has a stationary magnetic field. Motors, however, reverse the process and convert electrical energy into mechanical energy.

211. Name the basic types of DC generators, and compare AC and DC generator operation.

Components of a Basic DC Generator. You will notice in figure 2-9 that the components of the basic DC generator are very similar to those of the basic AC generator. The only difference is the use of commutator segments rather than slip rings. The commutator segments switch the connections to the external circuit each time the voltage induced in the armature changes polarity. Notice that both brushes ride on the same commutator, but they're connected to opposite sides of the commutator.

How DC Is Generated. The loop in figure 2-9 shows the conductor moving parallel to the magnetic field, so there's no voltage induced in the loop. Notice also that the brushes are across the opening between the commutator segments at this time. As the loop rotates through 90° from this position, a maximum voltage is induced in the conductor, causing current to flow in the loop from A to B, as shown in figure 2-10. This causes current to flow out of the left-hand brush, through the load in the direction indicated by the arrow, and back to the right-hand brush. When the loop reaches the 180° position, the induced voltage again becomes zero. Also, the commutator has now turned 180° and the brushes are again across the opening. As the loop rotates to the 270° position, a maximum voltage is induced in the loop, causing a current flow within the loop from B to A. Since the left-hand brush is now riding on commutator segment A, current will flow out of the left-hand brush, through the load in the direction indicated by the arrow, and back to the right-hand brush. Finally, as the loop continues to the 360° position, the induced voltage

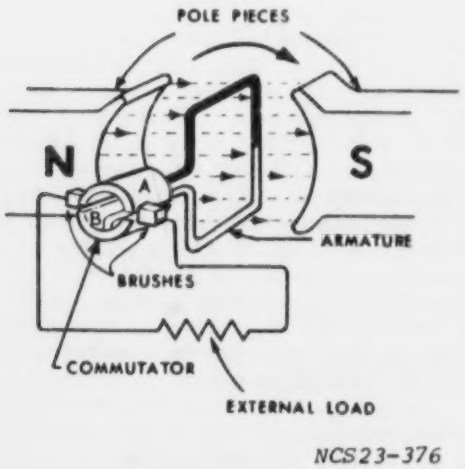


Figure 2-9. Basic DC generator components.

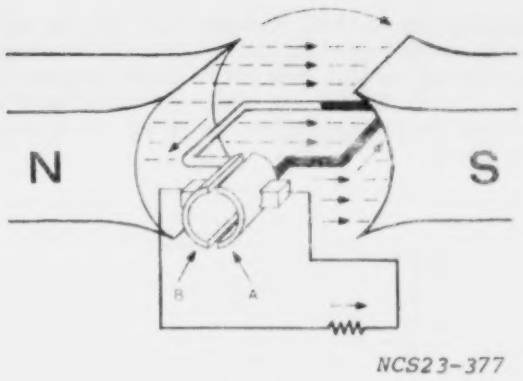


Figure 2-10. Current in a rotating loop.

again returns to zero. From our illustration, you can see that, although the current induced in the loop reverses for every 180° rotation of the loop, the commutator switches the external circuit so that the current through the external circuit remains in the same direction. The voltage across the load is plotted in figure 2-11. The voltage across the load does not reverse polarity, but it varies from zero to maximum. This is a pulsating voltage. A pulsating DC voltage is a DC output that periodically drops to zero. We can make the generator's DC output smoother by adding a second loop at 90° to the original loop. The commutator then has four segments. With this kind of armature, the induced voltage of one loop is at maximum while that in the other loop is zero. If the brushes are positioned properly, they furnish the maximum voltage to the external circuit during the time each loop is at maximum. To produce a DC voltage with smaller variations, we can simply add more loops.

Types of DC Generators. DC generators are series, shunt, or compound, depending on the relationship between the field and the armature windings. With the field coil and the armature windings in series (fig. 2-12,A), you have a *series generator*. Figure 2-12,B, shows the output voltage versus the load current. Notice that, without a load, no current can flow through the generator. The output voltage with zero load current results from residual magnetism in the pole pieces. As load current increases, field strength increases, the rotating armature coil cuts more magnetic lines, and output voltage increases. Notice that there is a rheostat in *parallel* with the field coil. This rheostat regulates the field current, thus controlling the generator output.

Figure 2-13,A, is a schematic diagram of a *shunt generator*. Note that the field coil is in parallel with the armature and load. Field current can flow when no load is connected. Figure 2-13,B, shows maximum output voltage with zero load current. A rheostat is placed in *series* with the field to control this generator output. Notice that in the shunt generator with a load connected (fig. 2-13,A), the current induced in the armature flows in two paths—part flows through the field coil branch, and part flows through the load. As the load current increases, the output voltage

decreases (fig. 2-13,B). Compare this with the series generator, where all of the current induced in the armature flows through the load. Note that the graphs in figures 2-12 and 2-13 show that the rated voltage and current values are the same, but above and below these values, characteristics vary greatly.

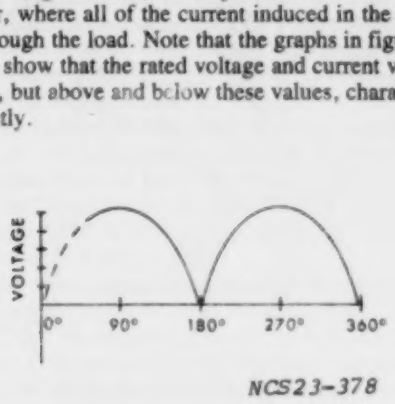


Figure 2-11. Voltage across the load.

The *compound DC generator* (fig. 2-14) has a series field winding and a shunt winding. It can build a desired voltage up without a load (shunt characteristic), and when a load is connected, field strength is increased (series characteristic). Adding the series winding to the shunt generator offsets the voltage decrease we get with just a shunt field. The compound generator has better regulation; that is, it has a more uniform output voltage with changing load, as you can see in figure 2-14.

Exercises (211):

1. What's the practical difference between a basic DC generator and an AC generator?

2. Name three types of DC generators.

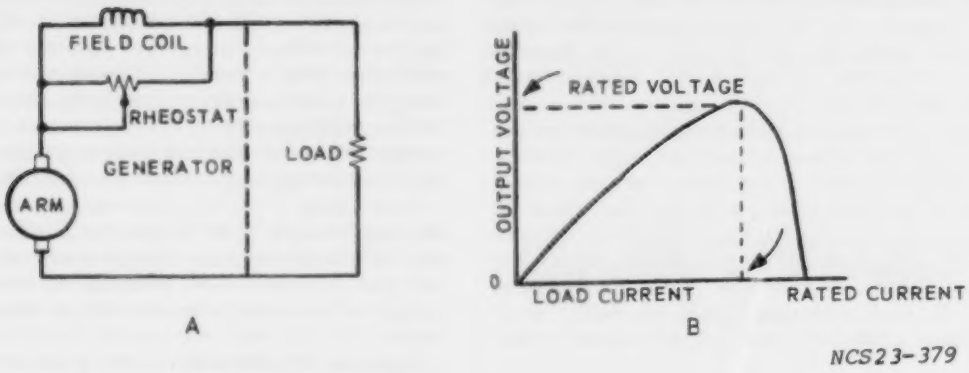


Figure 2-12. Series DC generator circuit and output.

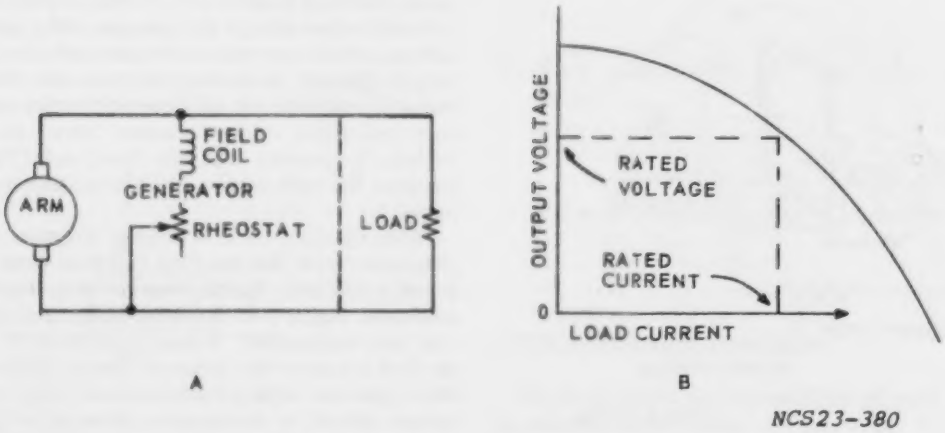


Figure 2-13. Shunt DC generator.

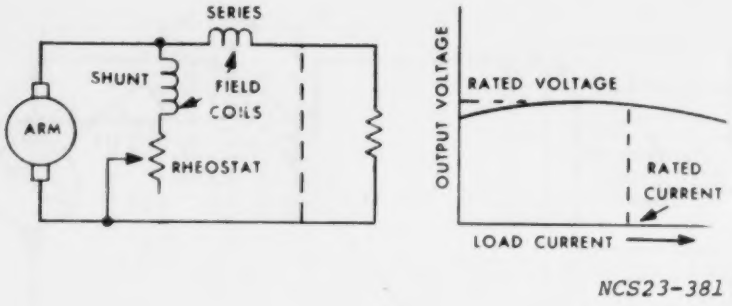


Figure 2-14. Compound DC generator.

3. Which type of DC generator gives the best voltage regulation? Why?

2-4. Inductance

We've discussed what AC is, how it is generated, and some of its characteristics. Now let's explore some of its effects in electrical circuits, starting with inductance and some of the terms we use in dealing with inductance.

212. Identify types of inductance, list the four physical factors that affect a coil's inductance values, and compute impedance.

Inductance is a property of a circuit that opposes any change in current flow. All circuits have this property, but the opposition takes place only when there is a change in current flow. Inductance does *not* oppose current flow, it only opposes a *change* in current flow. Where current is constantly changing, as in an AC circuit, opposition caused by inductance is always present. The symbol for inductance is the capital letter L.

Before we continue, let's mention the counter-electromotive force (CEMF) of motors. In motors, CEMF is the voltage induced in the armature as the rotating armature coils cut through the magnetic lines of the field. It is directly proportional to the speed of the armature—to the number of lines of force that are cut per second. Look now at figure 2-15 and let's see how AC fills the three induction requirements of a magnetic field, a conductor, and relative motion. Detail A shows a conductor with an alternating current applied from the generator. At time T0 (detail B), the current waveform is at zero, representing no current flow in the conductor, and there is no magnetic field. From T0 to T1, the current is increasing and is flowing from A to B in the conductor. This increase in current flow produces an expanding (or moving) magnetic field around the conductor (detail C). We now have a conductor, a magnetic field, and the relative motion necessary for induction.

When the current decreases from maximum to zero (during the interval T0 to T2), the magnetic field collapses and cuts the conductor in the opposite direction (detail D). We again have a conductor, a magnetic field, and relative motion. We have the same sequence of events during the interval T2 to T4, except that the current in the conductor flows from B to A and produces an opposite polarity to the magnetic field (details E and F). This makes the polarities of the induced voltage opposite. In all cases, the induced voltage opposes the change in current flow.

To increase the property of inductance, the conductor is formed into a loop or coil. In figure 2-16, a conductor forms 2 1/2 loops. Current flow through one loop produces a magnetic field that encircles the loops in the direction shown in detail A. As current increases, the magnetic field expands and cuts all loops (detail B). The current in every loop affects all other loops. The field cutting other loops has the effect of increasing the opposition to a current change. When current is increasing, energy from the AC generator builds up the magnetic field. When the current is decreasing, the magnetic field collapses and returns its energy to the circuit.

Self-Inductance. Let's look at some of the other terms you'll encounter in dealing with inductance. First, figures 2-15 and 2-16 show only one conductor, and the CEMF is induced in this conductor. This is *self-induction*, the process by which the magnetic field of a conductor (circuit) induces a CEMF in the conductor (circuit). Its symbol is the same as that for inductance, the letter L.

Mutual Inductance. Another type of induction is mutual induction, which induces a voltage in one circuit by varying the current in some other circuit. Mutual inductance, then, is the common property of two associated electric circuits, which determines, for a given rate of change of current in one of the circuits, the EMF induced in the other. Its symbol is the letter M. Figure 2-17 shows an AC generator furnishing power to coil A. Coil B is connected to a voltmeter. Notice that there is no physical connection between the two coils. As alternating current flows through coil A, it produces a magnetic field that is alternately expanding and collapsing. Each time the magnetic field builds up or collapses, it cuts across coil B.

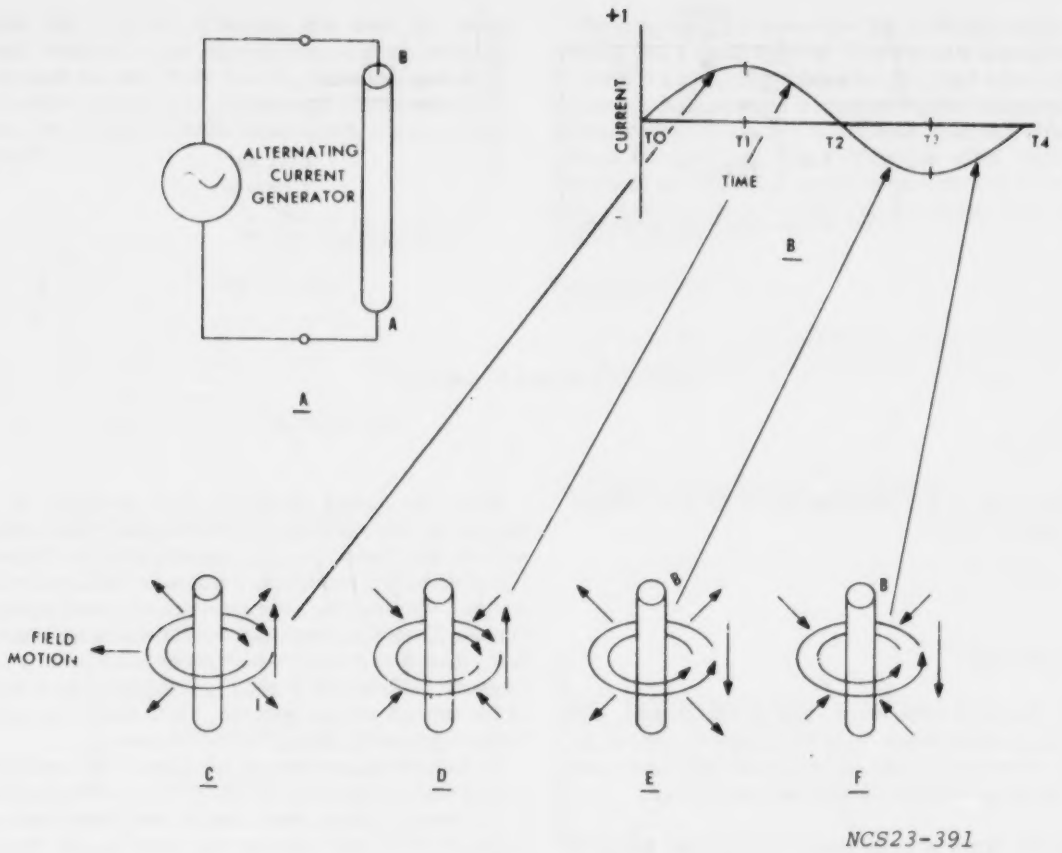


Figure 2–15. Alternating field for induction.

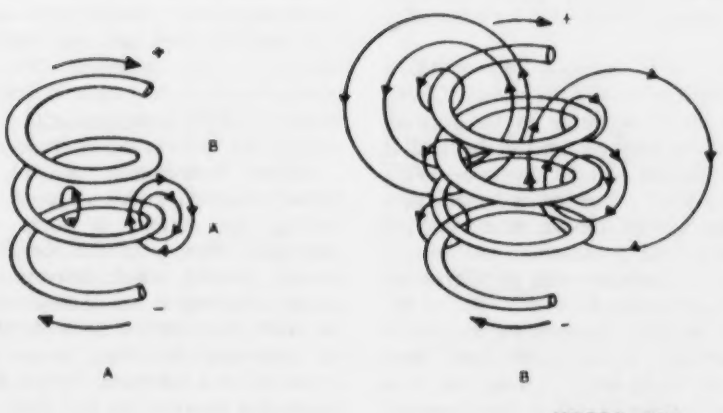


Figure 2–16. Increasing induction by coiling the conductor.

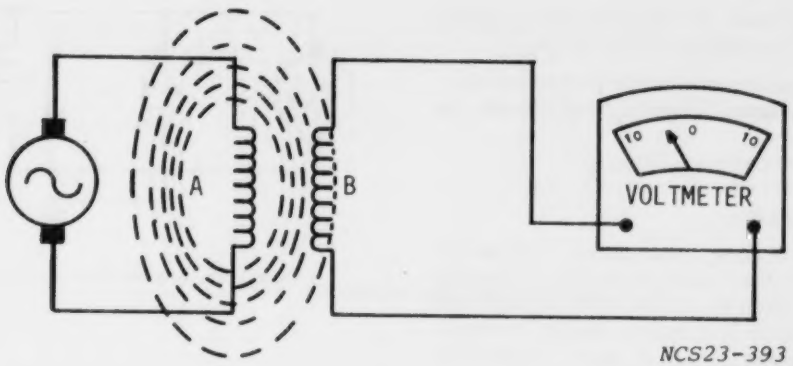


Figure 2–17. AC generator powering coil.

Again we've got the induction requirements of a magnetic field, a conductor, and motion. You can see that a voltage will be induced in coil B. This voltage will have one polarity when a magnetic field is expanding and the opposite polarity when the same magnetic field is collapsing. This alternating voltage will cause current to flow through the voltmeter. The voltage induced in coil B by a varying current in coil A is an application of mutual induction. The unit of measurement of inductance is the "henry," the inductance in a circuit that induces an EMF of 1 volt when the current is changing at a rate of 1 ampere per second. Its symbol is the small letter h.

Flux Linkage. Flux linkage is the interlocking of magnetic lines of force. It is those magnetic lines around one coil or wire that link another coil or wire. The ratio of the flux lines originating in one coil that cut a second coil to the total number of lines developed around the first coil gives us a new term, "coefficient of coupling."

Factors Affecting Inductance. Four physical factors that affect the inductance of a single-layer coil are the number of turns in the coil, the diameter of the coil, the coil length, and the type of material used for the core. Increasing the number of turns in the coil has the same effect as increasing the number of conductors in the field of a basic generator. In the basic generator, it increases the output; in a coil, it increases the CEMF. Thus, doubling the number of turns increases the inductance of the coil by a factor of about 4.

The second factor is the coil diameter. Let's say we've got two coils with the same number of turns in conductors of the same diameter. The cores are the same length, but one is much larger than the other, providing an easier path for the magnetic flux. Again we've increased the magnetic field's strength, and since inductance increases directly with the cross-sectional area of the core, doubling the radius of our coil increases the inductance by a factor of 4.

The third factor in the coil's inductance is its length. Again let's say that we've got two coils with the same number of turns in conductors of the same diameter. This time the cores have the same cross-sectional area, but one is much longer than the other, with its conductor's turns spaced farther apart. The coil with the longer core has few flux linkages because of the space between turns, so it has low inductance. The other coil has the same number of turns, but they're closely spaced, increasing the flux linkage—and the coil's inductance. The longer coil will have less inductance; doubling the length of a coil halves its inductance.

The fourth physical factor is the type of core material. For example, a soft-iron magnetic core provides a better path for magnetic lines of force than a nonmagnetic core (such as air). Its high permeability gives less reluctance to the magnetic flux, resulting in more magnetic lines of force. This increase in the magnetic field increases the number of lines of force cutting each loop of the coil, this increasing the coil's inductance. This factor can be affected by the type of coil winding you use. A coil that's closely spaced and wound in layers maximizes the flux linkage, producing larger inductance values than a single-layer wound coil of the same size.

Calculating Inductance. The unit of inductance (L) of a coil is the henry (h). A coil that develops a CEMF of 1 volt when the current is changing at the rate of 1 ampere per second has an inductance of 1 henry. From the physical factors that affect inductance, we can develop an expression that approximates a unit of inductance:

$$L = N_2 \frac{\mu A}{l}$$

where:

L = inductance.
N = number of turns.
A = cross-sectional area of the core.
μ = permeability of the core material.
l = length of coil.

To make a practical formula, this equation must be applied by a practical constant that depends on five things:

a. Unit of linear measurement (inches or centimeters).
b. Unit of inductance (henries, millihenries, or microhenries).
c. Coil construction (single or multilayered).
d. Ratio of the length to the diameter of the coil.
e. Percent of flux linkage.

Many times you will come across circuits with several inductors, connected either in series or parallel. Computing total inductance in a series or parallel circuit is much like computing total resistance in a series or parallel resistance circuit. Figure 2-18 shows coils A, B, and C connected in series in an AC circuit. Coil B introduces a certain amount of inductance, coil A adds to this inductance, and coil C adds to the total of A and B. To find the total inductance in a series circuit, you add the inductance of all the coils.

Now let's see what happens when we have three coils in parallel (fig. 2-19). The coils X, Y, and Z provide three paths for current. The current that goes through coil X is opposed only by the inductance of coil X. The same is true of the current going through coils Y and Z. The formula for total inductance of a parallel circuit is:

$$Lt = \frac{1}{\frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3} + \cdots + LN}$$

Symbols for Inductors. Figure 2-20 shows the symbols for three inductors: A has an air core, B has a fixed magnetic core, and C has a variable core. The air-core inductor is often used in RF circuits, while the fixed magnetic core inductor is used in many AF and power circuits. The variable magnetic inductor is used in both AF and RF circuits. Since power frequencies of 60 and 400 hertz are within the AF range, power and audio frequency inductors are similar in construction. The main differences between them are the type of core material and the size of the wire in the coil. The power inductor is wound with larger wire to handle larger amounts of current than the audio-frequency inductor. Both have laminated cores, but core losses are held to a minimum in the audio inductor by more laminations and thinner plates. The RF inductor is used in circuits with frequencies above 20,000 hertz. The RF inductor normally has an air core, but it may have a fixed or variable magnetic core.

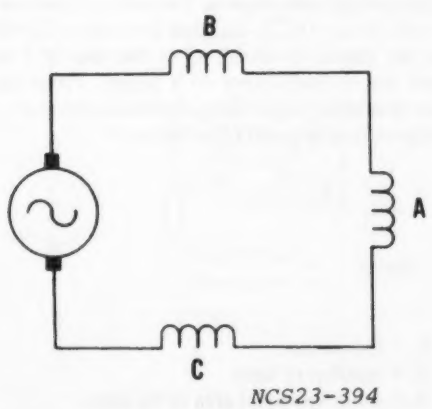


Figure 2–18. Induction effects of coils in series.

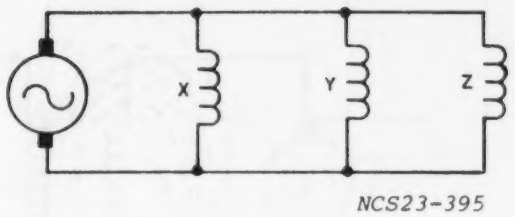


Figure 2–19. Induction effects of coils in parallel.

Figure 2–20. Symbols for inductors.

Voltage and Current Relationship in Inductors. Since an inductor opposes a change in current flow, you can see that an inductor has very little effect on direct current. Since an AC sine wave is continually changing, the magnetic field in an AC circuit is continually changing, generating a CEMF that continually opposes the change in current. Let's analyze the effects of an inductor in a circuit with an AC source.

Inductor Connected to an AC Source. Figure 2-21 is an inductor connected to an AC source. The graph shows the relationship between the current (I) and the voltage (E) developed across an inductor. The solid line represents the current across the inductor, and the dotted line is the voltage across the inductor. This voltage (E) is actually a CEMF developed as the current's magnetic field expands and collapses. At the start time (T0), the rate of change is maximum and the voltage (CEMF) is maximum. As the current's rate of change gradually decreases, from T0 to T1, the voltage induced decreases. At T1, the current stops increasing. Now there is zero rate of change, and the induced voltage decreases. As the current flow decreases (T1 to T2), the magnetic field collapses and the polarity of voltage induced across the inductor reverses. Notice that at T1, with zero rate of change, E=0. As the current's rate of change increases to maximum at T2 (where even the direction of current flow changes), E is maximum, with reversed polarity from T0 (−4 units).

Let's assume that current flow through the coil is from B to A during T0 to T2. The current through the coil forms an electromagnet that has one polarity. During the next half-

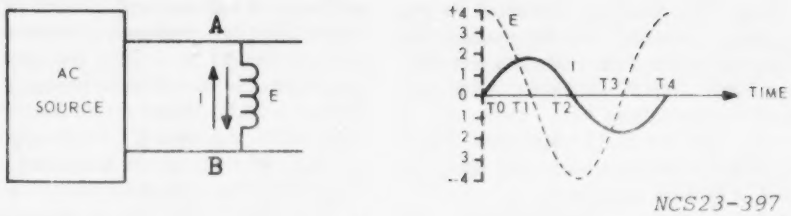


Figure 2–21. Inductors with applied sine wave.

cycle (T2 to T4), current flows from A to B and the electromagnet formed by the current has the opposite polarity. The electromagnet's polarity depends on current flow and has no relation to the voltage induced. The maximum rate of current change takes place when current passes through zero at T0, T2, and T4. As the current decreases to zero and reverses its direction, the induced voltage reaches its peak and then starts decreasing. When the rate of current change decreases to zero at T1 and T3, there is no change in polarity and zero voltage is induced in the coil.

In all cases, the amplitude of the induced voltage is determined by the rate of change of current flow. The polarity of the induced voltage is determined by the direction of current flow and whether it is increasing or decreasing. The induced voltage opposes any change in current flow. If current is increasing, induced voltage opposes the increase; if current is decreasing, induced voltage opposes the decrease. Of special interest is the fact that, for the sine wave of current, there is a sine wave of voltage. The current leads the voltage by 90°.

Inductive Reactance. Since the current in a purely inductive circuit lags the voltage by 90°, the magnetic field expands and collapses, so it reacts and dissipates no power. That's why we call the opposition reactance, and we use the symbol X. Reactance of coil L, we call *inductive reactance* X_L, the opposition to current flow offered by that circuit's inductance. We can calculate the inductive reactance using the formula

$$X_L = 2 \pi fL$$

where X_L = inductive reactance in ohms (dissipates no power), 2π = 6.28, f=frequency in hertz, and L=inductance in henries. As you can see, the two variables that affect inductive reactance are the inductance and the frequency. Since inductive reactance is opposition to current flow, we can use the same unit of measure we use for resistance. Inductive reactance X_L, then, is measured in ohms.

Exercises (212):

1. Define flux linkage.
2. List the four primary physical factors that affect a single-layer coil's inductance.
3. Does an air, or soft-iron, core have more reluctance to inductance?
4. What's the total impedance of a circuit with coils of 10 henries, 20 henries, and 30 henries connected in parallel?
5. What's the symbol for an inductor with fixed magnetic core?
6. What's the unit of measurement for inductive reactance?
7. What symbol is used for for inductive reactance?

2-5. Transformers

A transformer does just what its name says. It transfers electrical energy from one circuit to another by mutual induction.

213. Name the types of transformers, define terms, and cite structural and operational details related to them.

Transformer Construction. A simple transformer has two wire coils, or windings, on some type of core. An AC source is connected to one of the windings, and a load is

connected to the other. The winding connected to the source is called the primary winding, and the winding that supplies energy to the load is called the secondary winding. A transformer may have several secondary windings. Frequently, additional connections are made to a transformer winding between the end connections. These additional connections are called taps, and a tap placed at the center of a winding is called a center tap.

Transformers use various materials for their cores. The air-core transformer is used often in circuits carrying radio-frequency energy, though radio-frequency transformers also use powdered iron, brass, and aluminum cores. Transformers used in low-frequency circuits require a core of low-reluctance magnetic material to concentrate the field about the windings. This type of transformer is called an iron-core transformer. Audio and power transformers are of the iron-core type. Iron cores are often fabricated from a number of thin silicon steel stampings called laminations, which are covered with an insulating varnish before they are assembled. The schematic symbols for the air-core, iron-core, and multiple-secondary transformers are shown in figure 2-22. Notice that the center tap is the multiple-secondary-winding transformer.

Step-Up and Step-Down Turns Ratios. The transformer in figure 2-23,A, has a 10-turn primary and a 2-turn secondary winding. The ratio of the number of turns in the primary to the turns in the secondary is called the turns ratio. If an input of 10 volts at 60 hertz is applied to the primary winding and no load is connected to the secondary winding, the primary acts as a simple inductor. The current flowing in the primary will depend on the applied voltage (amplitude and frequency) and the inductive reactance of the primary. This current produces a magnetic field, which cuts the primary and secondary as it expands and collapses. This action produces a CEMF in the primary that nearly equals the applied voltage, and it induces a voltage in the secondary (mutual inductance). The amplitude of the voltage induced into each turn of the secondary will be identical to the CEMF produced in each turn of the primary. With 10 volts applied across 10 turns (fig. 2-23,A), a CEMF of nearly 1 volt per turn will develop, so a 2-turn secondary will have an induced voltage of 2 volts (1 volt per turn). A turns ratio of 10 (primary) to 2 (secondary) has produced a stepdown in voltage from 10 volts (primary) to 2 volts (secondary), or 5 to 1. This transformer is described as having a stepdown turns ratio. Figure 2-23,B, shows a transformer with a step-up turns ratio of 1:4. An input of 10 volts applied to the primary will produce 40 volts in the secondary. Notice that the turns ratio equals the voltage ratio in all cases.

The extent to which the magnetic lines of the primary cut across the secondary is expressed as a "coefficient of coupling." We assumed that the transformers in figure 2-23 had a coefficient of coupling of 1. This means that all of the magnetic lines of the primary link the secondary. That is, 100 percent of the flux lines produced by the primary winding cut the secondary winding. A coefficient of coupling of .9 means that 90 percent of the flux lines produced by the primary cut the secondary. A coefficient of coupling of less than 1 reduces the voltage induced in the secondary.

Transformer Operation with Loaded Secondary. Up to this point we've considered induced voltage only. As we've seen, with a load connected to the transformer's secondary winding, current flows in the secondary. The magnetic field produced by current in the secondary interacts with the primary field. This interaction is truly mutual inductance, with both primary and secondary currents inducing voltages. The magnetic field produced by secondary current is in direct opposition to the primary magnetic field and cancels some of it. This reduces CEMF and, as a result, primary current increases to nearly reestablish the primary field. To summarize, as current increases (with increased load) in the secondary, primary current increases.

The total power available from a transformer secondary must come from the source that supplies the primary. Remember, a transformer does not generate power; it merely transfers power from a primary circuit to a secondary circuit. If the transformer is 100 percent efficient, total primary power equals secondary power. Figure 2-24,A, shows a 100-ohm load connected to the secondary. The transformer has a step-up ratio of 1:10. Ten volts applied to the primary will produce 100 volts in the

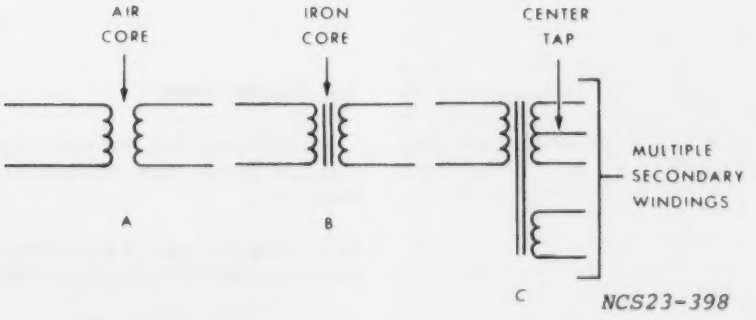


Figure 2-22. Transformer symbols.

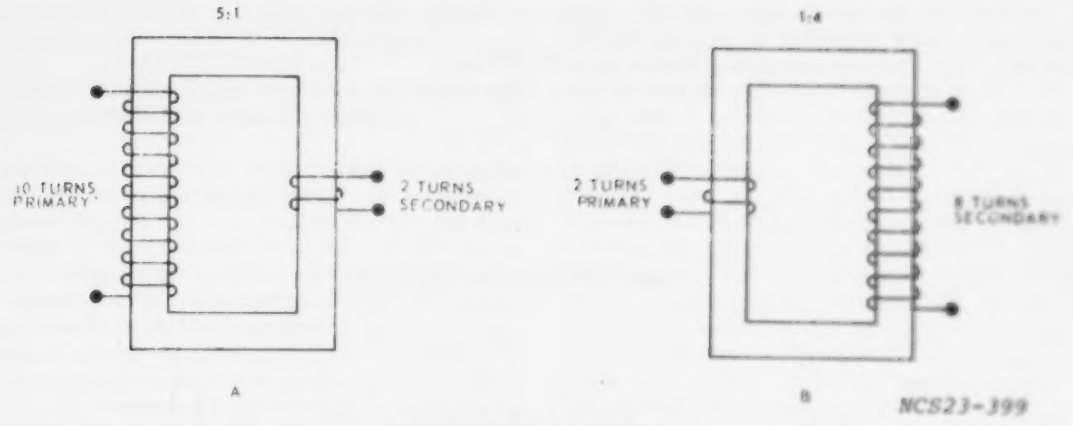


Figure 2-23. Transformer action.

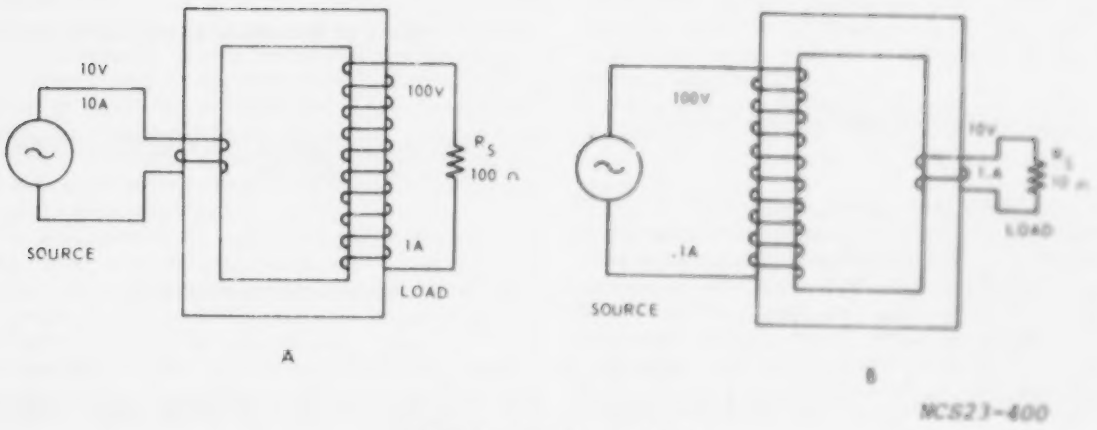


Figure 2-24. Transformer with load.

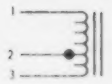
secondary. Current through the 100-ohm load will be 1 ampere. Power consumed in the load is 100 watts ($P = I \times E$). Notice that we have a step-up in voltage (1:10) and a stepdown in current (10:1). Power supplied to the load comes from the source, and there are no losses in the coupling. This transformer is 100 percent efficient because output power equals input power.

Practical transformers, although highly efficient, are not perfect devices. They range from 80 to 98 percent efficiency. Primary power must be slightly greater than secondary power to offset the decrease in efficiency. The losses associated with transformers are the same as the losses for inductors. Efficiency can be computed by dividing transformer output power by input power.

Now, refer to figure 2-24,B. The transformer has a stepdown turns ratio of 10:1. One hundred volts applied to the primary will induce 10 volts in the secondary. If we use a 10-ohm load connected to the secondary, we will have 1 ampere of current. Power consumed by the load is 10 watts. Now the source must supply 10 watts of power. With 100 volts, the current needed to provide this power is .1 ampere. Notice that we have a stepdown voltage but a step-up in current. The current is increased by the same ratio as the voltage decreases. Again, our calculations assume a 100-percent efficient transformer.

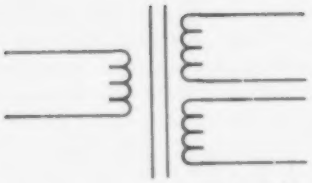
Types of Transformers. There are four types of transformers: autotransformers, power transformers, audio transformers, and RF transformers. The *autotransformer* is a special type of transformer. By definition, it is one with a single winding (electrically) which is tapped. The whole winding may be used as the primary and part as a secondary (stepdown) or part of the winding may be used as the secondary (step-up). Figure 2-25 shows the symbol and several possible connections. For example, using terminals 1 and 2 as the primary, you can have a step-up condition by using terminals 1 and 3 as the secondary. (Note, in all cases, there's a complete circuit between the primary and secondary windings. Autotransformers are normally used in power circuits, but they may be designed for audio- or radio-frequency (RF) use. Figure 2-26 shows the symbol for

PRIMARY	SECONDARY	
	STEP UP	STEP DOWN
1-2	1-3	2-3
1-3		1-2 2-3
2-3	1-3 1-2	



NCS23-401

Figure 2-25. Symbol for autotransformers.



NCS23-402

Figure 2-26. Symbol for power and audio transformers.

NCS23-403

Figure 2-27. Symbol for air-core RF transformers.

power and audio transformers. The symbol for an RF autotransformer is the same except that it may not indicate an iron core. The RF autotransformer often has an air core.

Power transformers are often made with two or more secondary windings. Thus, one transformer can provide several voltage level outputs. Figure 2-26 is a typical power transformer. The secondaries give a wide selection of voltages and currents. Power transformers usually operate on frequencies from 50 to 1600 hertz and handle relatively large amounts of power. The *audio transformer* resembles a power transformer in appearance, but it has several internal refinements. The core material is carefully selected, and special techniques are used to make the windings. Audio transformers are designed to operate over the audio range of 20 to 20,000 hertz. They are available with multiple primaries and/or secondaries. *RF transformers* operate in ranges from 10 kHz to 300,000 MHz. The symbol for an air-core RF transformer is shown in figure 2-27.

Exercises (213):

1. What type of core material do transformers used in low-frequency circuits need?

2. What type of ratio does a transformer have if, when you apply 10 volts to the primary, the voltage read across the secondary is 2 volts?

3. What equation indicates that a transformer's turns ratio equals its voltage ratio?

4. What's the coefficient of coupling?

5. What does it mean if a transformer has a .9 coefficient of coupling?

6. In reference to power in a transformer, what does 100-percent efficient mean?

7. What is the relationship between a transformer's voltage and current magnitude?

8. Name the four types of transformers.

2-6. Capacitance

A capacitor is an electrical device whose phase effect on current flow in an AC circuit is just the opposite of an

inductive circuit. Instead of lagging, its current is leading the voltage by approximately 90 electrical degrees.

214. Define capacitors and capacitive reactance, and specify factors that affect capacitive circuits.

Capacitor. In an electrical circuit, a capacitor serves the purpose of storing electrical energy. A capacitor is sometimes referred to as a condenser, but the term "capacitor" is more common. Since this unit can store an electrical charge, it has a certain *capacity*. A capacitor is two conducting surfaces separated by an insulating material known as the dielectric. Such materials as glass, air, mica, wax paper, and oil are commonly used as dielectrics. A capacitor's principal feature is its ability to store a quantity of electricity. To illustrate this point, figure 2-28 represents a simple capacitive DC circuit. If there is no charge on plates A and B before the key is closed, they will be at the same (zero) potential. When the switch is closed, however, the battery will act as a pump—the positive side drawing electrons from plate B, giving it a positive charge, and the negative side placing an excess of electrons on plate A, making it negative. During the interval that the electrons are moving from B to A, current flows in the circuit. This flow is at maximum the instant the switch is closed and continuously decreases until it reaches zero and the difference in potential of the charges on plates A and B is the same as the battery's EMF. If the switch is now opened, the plates retain their charges.

We could remove the battery and put a conductor in its place. Then, if we close the switch, current will flow from A to B. This current will again be at maximum the instant the switch is closed. It will decrease to zero when the difference in potential between the plates is zero.

Capacitance. Like the relationship between inductor and inductance, capacitance must not be confused with capacitor; capacitance is an ability demonstrated by a device called a capacitor. A capacitor's capacitance depends on its physical makeup, not on voltage, frequency, or current. There are three factors we can vary to affect capacitance: the area of the plates, the distance between the plates, and the material used for the dielectric. If we increase the area of the plates, there's more surface on which to store electrons, and the capacitance increases. (Notice that the capacitance depends on the area of the plates and not upon their thickness.) On the other hand, the greater the distance between the plates, the less capacitance there will be. As the distance between two forces is increased, the resulting effort exerted between them decreases in direct proportion to the square of the distance.

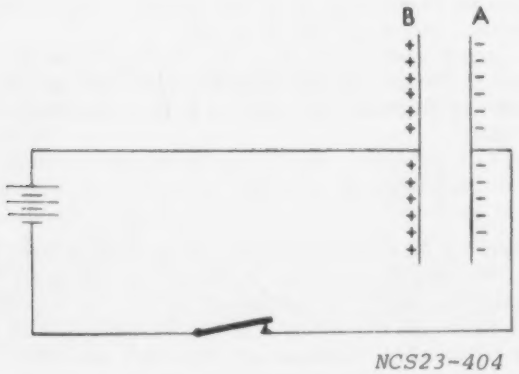


Figure 2-28. Capacitor in a DC circuit.

Capacitors are commonly rated for their capacitance, their working voltage, and their peak voltage. The working voltage is the amount of voltage that can be applied continuously without destroying the capacitor. Peak voltage is the largest amount of voltage that can be applied to any given time without causing a breakdown. The unit of measurement for capacitance is the *farad*, or the amount of capacitance that will store 1 coulomb at a potential of 1 volt. You can see that a capacitor with a capacitance of 1 farad would be a very large unit; in fact, it would fill a 10- by 12-foot room. It is quite evident that a capacitor of this size is impractical. Because of the size factor, small capacitors that are rated in microfarads (μFs) are used. Such capacitors can be made small enough to be practical in intricate integrated systems.

Capacitors in Practical Circuits. To get the right capacitance in a circuit, capacitors are often connected in parallel and sometimes in series. The units may be placed quite close to each other without affecting each other to any extent. If you don't need any more capacitance than is available in a single capacitor, you can connect more units in parallel, and the total capacitance is the sum of the individual capacitances. Capacitors connected in series will have a total capacitance of less than that of the smallest capacitor in the series. If all the capacitors have equal capacitance, you can find the total value by dividing the capacitance of one capacitor by the number of capacitors. Thus:

$$C_t = \frac{\text{value of one capacitor}}{\text{number of capacitors}}, \text{ or } C_t = \frac{C}{N}$$

What if we connect two capacitors of different values in series? We can find the capacitance by multiplying the two values and dividing the product by the sum of the capacitive values, thus:

$$C_t = \frac{C1 \times C2}{C1 + C2}$$

When we put three unlike capacitors in series, we find the total capacitance by the reciprocal formula:

$$C_t = \frac{1}{\frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3}}$$

We find the total capacitance of parallel circuits by adding the values of all capacitors.

Capacitive Reactance. When a capacitor is connected into a circuit to which AC is applied, it will be charged in one direction and then in the other. In this case, the electrons move back and forth like an alternating current at the frequency of the applied voltage. Although the current

of the circuit appears to flow through the capacitor, it actually does not—but the effect is the same. An AC ammeter placed in such a circuit will indicate the amount of current flow the same way it would if the capacitor were not in the circuit, but the amount of current flow will be less. This indicates that the capacitor does offer opposition to AC. This opposition is called capacitive reactance, the opposing current flow due to a capacitor in the circuit. X is the symbol for reactance, and since a capacitor is a reactor, we use the symbol XC for capacitive reactance. Like all other forms of opposition to current flow, it's measured in ohms. We find it with the formula:

$$XC = \frac{1}{2\pi fC}$$

where

$\pi = 3.14$

f = frequency (hertz

C = capacitance (in farads)

You can see by this formula that, as frequency increases, the capacitive reactance decreases.

Exercises (214):

1. State the purpose of a capacitor.

2. What materials are used as dielectrics?

3. What three factors affect the capacitance of a capacitor?

4. How does connecting two capacitors of different values in series affect the circuit capacitance?

5. When a capacitor is connected in an AC circuit, how it charged?

6. What is capacitive reactance? How is it measured?

2-7. Resistive and Reactive Circuits

Strange things happen when alternating current is applied to a circuit with resistors, capacitors, and inductors. Since the current leads the voltage in the capacitor and lags the voltage in an inductor, all sorts of current phase angles appear when resistors, capacitors, and inductors are connected in series, parallel, or series-parallel. The simplest of these combinations is a series-resistive circuit. It will be a little easier if we start with this simple circuit and work toward the more complex AC circuits.

215. Specify the voltage and current relations in AC circuits with resistance, inductance, and capacitance.

Resistive Circuits. When an alternating voltage is applied to a series circuit with resistance only, the current and voltage are in phase. One way to show the in-phase relationship is by sine waves. The value of the current in the circuit is sinusoidal and is maximum when the voltage is maximum. Another way to show the same relationship is by vector diagram. The value of vectors in studying the phase of currents and voltages will become more apparent as we go. In the vector diagram in figure 2-29, the current and voltage vectors coincide, showing that they are in phase. Since a resistor presents the same opposition to AC it does to DC, current flow in an AC circuit with only resistance is equal to the voltage divided by the impedance. Impedance is total opposition to current flow, so in an AC circuit with only resistance, resistance and impedance are the same thing. Ohm's law for AC is:

$$I = \frac{E}{Z}$$

where I is current in amperes, E is voltage in volts, and Z is impedance in ohms. In some AC circuits, impedance includes not only resistance but also capacitive or inductive reactance or both. (We'll cover relationships among Z, R, and X_L or X_c later.)

In figure 2-30, the voltage, E, is the reference vector and I is drawn upward from O. In vector representation, the position of I is called the leading portion. One point here that has a bearing on power is that the product of E and I is alternately positive and negative. Several of the figures show the power available so that you can see a relationship between current, voltage, and power.

Current leads voltage in a capacitive circuit (as we saw earlier) because of capacitive reactance, indicated as X_c and, like resistance, measured in ohms by the Ohm's law formula:

$$I = \frac{E}{Z} = \frac{E}{X_c}$$

where I is the current in amperes, E the EMF in volts, and X_c the capacitive reactance in ohms. The impedance in a capacitive circuit is represented by X_c, the capacitive reactance. So far, we've seen that impedance in an AC circuit includes resistance and capacitive reactance. The formula for relationships among current, voltage, and impedance in an AC circuit is called Ohm's law for AC. It

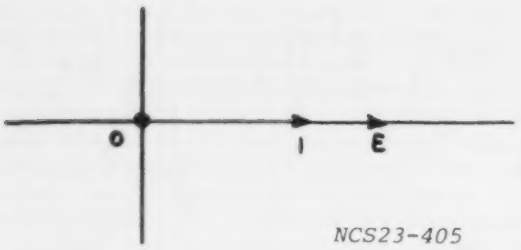


Figure 2-29. Resistive circuit vector representation.

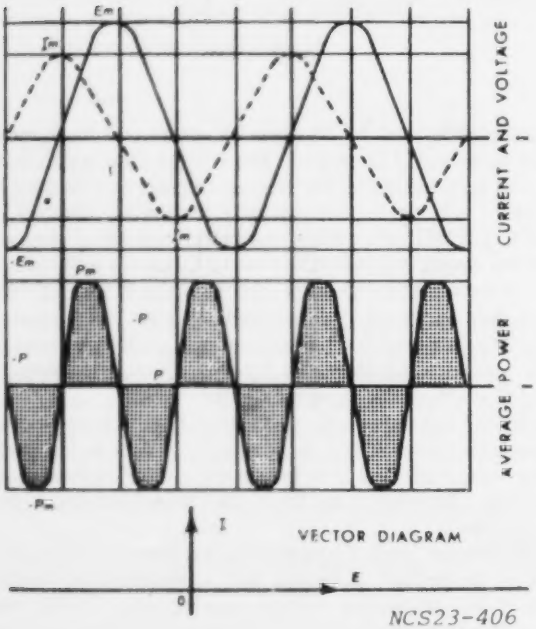


Figure 2-30. Capacitive circuit current, voltage, and power.

is based on effective values, but it's equally true for maximum, average, or instantaneous values of current and voltage.

Resistive and Inductive Circuits. In a series AC circuit with both resistance and inductance, the voltage across the inductance leads the current by 90° and the voltage across the resistance is in phase with the current. Because of the phase difference caused by the inductive component, total impedance in the circuit is not the arithmetic sum of the resistance and the inductive reactance, but their vector sum, expressed by the formula:

$$Z = \sqrt{R^2 + X_L^2}$$

Similarly, the total voltage drop in the circuit is the vector sum of the individual voltage drops expressed by the formula:

$$E = \sqrt{E_R^2 + E_L^2}$$

Certain geometrical relationships of a vector diagram involving the circuit components will help you understand how these formulas are derived. Figure 2-31 shows a circuit with resistance in series with an inductive reactance. In this vector diagram, the current I is the reference vector or the 00 line. (This is a series circuit, so current is the same throughout.) Since the voltage across R is in phase with the current, it is drawn to coincide with I. Because the voltage across the inductance is equal to I_{XL} and because it leads the current I by 90°, it is drawn perpendicular to ER. The resultant of these two EMFs in series, according to the parallelogram of forces method, is their vector sum. The parallelogram's diagonal, EZ, is the total voltage drop in the circuit. By Kirchhoff's laws, it's equal to the applied voltage, E. We can find the magnitude of E from the right triangle with legs ER and EL and hypotenuse EZ, which is equal to E:

$$E = \sqrt{E_R^2 + E_L^2}$$

Since the voltage drop across ER is equal to IR and the drop across L is equal to IXL, it's evident that the total voltage drop is:

$$E = \sqrt{(IR)^2 + (IX_L)^2}$$

By factoring:

$$E = \sqrt{I^2(R^2 + X_L^2)}$$

By taking the squart root:

$$E = I\sqrt{R^2 + X_L^2}$$

But, since E = IZ, the total impedance Z is:

$$Z = \sqrt{R^2 + X_L^2}$$

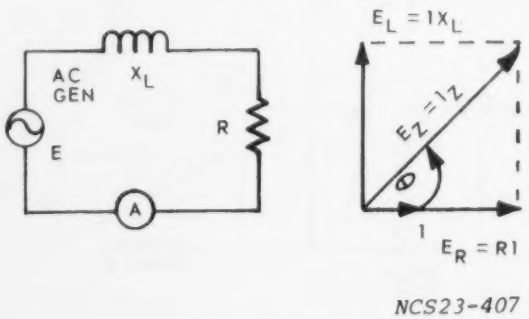


Figure 2-31. Circuit and vector diagram.

Resistive and Capacitive Circuits. In these circuits, as in a resistive-inductive circuit, resistance and capacitance don't add arithmetically, but vectorially. With circuit resistance and capacitance connected in series, total opposition to current flow is:

$$Z = \sqrt{R^2 + X_c^2}$$

To find the effective voltage from the out-of-phase relationship:

$$Z = \sqrt{E_R^2 + E_c^2}$$

Both of these formulas are easily proved by the impedance triangle and the parallelogram force method of vector representation shown in figure 2-32. The method is much like that used in resistive-inductive circuits.

Series Resonance. You know that the effective reactance in a series circuit with both inductive and capacitive reactances is their difference. The circuit may act capacitively or inductively, depending on the larger reactance. This fact expressed mathematically is $Z = R + (X_L - X_c)$. Since X_c decreases and X_L increases with an increase in frequency, there is a *resonant frequency* at which a given coil and capacitor have equal reactances. The condition of a series circuit with $X_c = X_L$ is called *series resonance*. At series resonance, the impedance is the resistance only. Since there is zero reactance, the current is in phase with the voltage, and since the only impedance is the resistance, the current is maximum at resonance.

In a series-resonant circuit with no resistance, if L (inductance) is in henries and C (capacitance) is in farads, we find the resonant frequency in hertz by the equation:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

At frequencies above resonance, a circuit's inductive reactance is greater than its capacitance and current lags applied voltage. The circuit is said to be inductive. Below resonance, capacitive reactance is greater than inductive reactance and the current leads the voltage. The circuit is capacitive. In the series-resonant circuit of figure 2-33,

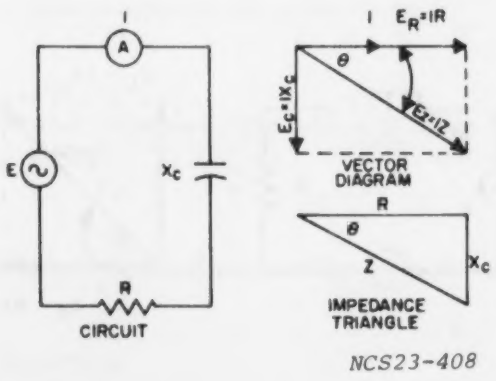


Figure 2–32. Series AC resistance and capacitance.

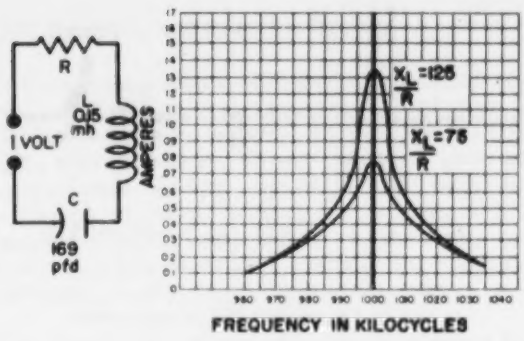


Figure 2–33. Series resonance.

reactances X_L and X_c are each 940 ohms and the current flow is about 0.133 ampere. The voltage drop across both E_L and E_c is 125 volts. The voltage drop across resistance R is only 1 volt, the applied voltage in the circuit. Voltages E_c and E_L are 180° out of phase and cancel each other when we add the circuit voltages. The ratio of E_L (or E_c) to E_R is 1:5; this is known as the Q of the circuit. Since R is mostly the resistance of the coil, you'll usually find the coil resistance called Q. The Q of a coil is the ratio of X_L to R at resonance. The second curve shown in figure 2-33 is for a lower Q circuit, of 75, due to a greater R in the circuit.

High-Q coils are preferred to low-Q coils, especially at resonance, because they let high current flow to the load, since very little power is lost in the coil's low-resistance winding. Remember, the lower the internal resistance, the greater the Q.

Resistance and Capacitance in Parallel Circuits. When we connect a resistor and a capacitor in parallel across an alternating voltage source, (fig. 2-34), the capacitor introduces capacitive reactance into the circuit as it does in a series AC circuit, but with a somewhat different action. In any parallel circuit, the voltage across the resistive and capacitive branches equal each other and equal the applied voltage. The current in the resistive branch is in phase with the applied voltage and equal to the applied voltage divided by the resistor's resistance, but the current and voltage through the capacitive branch are not in phase.

As you recall, current leads voltage in a purely capacitive circuit by 90°. The best way to understand how these currents and voltages act is with vector diagrams and sine waves. Notice first that the vector diagram in figure 2-34 differs from the series resistive-capacitive circuit we just saw. The most important difference comes from the fact that a parallel circuit's voltage is the same in all parts of the circuit. *The voltage, therefore, is used as the reference vector and not the current, as in a series circuit.*

All other vectors are drawn with reference to the voltage vector, which can be labeled E_a, E_R, or E_c, because they're all equal and in phase. The resistor's current is in phase with the applied voltage, so it coincides with the voltage

vector. Since current through the capacitor leads applied voltage by 90°, we draw it perpendicularly upward from the voltage vector. The circuit's total current is represented by the diagonal of a parallelogram with these sides. Always remember—a parallel AC circuit's total current is not the algebraic sum, but the vector sum, of its branch circuits.

Resistance, Inductance, and Capacitance. When both inductance and capacitance are in combination with resistance in parallel circuits, the computations are longer, but no harder, than for circuits with only resistance and capacitance. Let's find the total current in figure 2-35. We know it's the vector sum of the individual branch currents. The current in the resistive branch is in phase with the applied voltage, so it's indicative of the true power consumption. The inductive current lags the applied voltage by 90°, and the capacitive current leads it by 90°, so their effect is exactly opposite. Now let's find the branch currents by substituting R = 6 ohms, X_c = 24 ohms, and X_L = 12 ohms in the Ohms law formula:

$$I = 12 \text{ ohms}$$

$$I_R = \frac{E}{Z}$$

$$I_c = \frac{48}{6} = 8 \text{ amperes}$$

$$I_t = \frac{48}{12} = 4 \text{ amperes}$$

The voltage vector is our reference for the vector diagram of this circuit, so we lay it out first, along the horizontal scale to the right, as in the last circuit. Since the current in the resistive branch is in phase with the applied voltage, we lay out I_R along the voltage vector. Since the capacitor current leads the applied voltage by 90°, we draw I_c perpendicularly upward from the starting point of the voltage vector. Now we construct the vector for the current flow through the inductance. As you recall, the current flowing in a pure inductance lags the voltage 90°, so we draw I_L perpendicularly downward from the starting point of the voltage vector. The resultant of these two vectors is the open arrow in figure 2-35.

Since the capacitor current is 180° out of phase with the inductor current, we can combine them arithmetically. Since this circuit's inductor current is greater than its capacitor current, their resultant ($I_L - I_c$) is smaller than I_L, and this inductive current lags the applied voltage. Our next step is to find the resultant of this current ($I_L - I_c$) and I_R by completing the parallelogram between their vectors. The diagonal of this parallelogram is I_t, the circuit's total current. The angular displacement between vector I_t and vector E is the phase angle. The cosine of this angle, I_R/I_t, is the power factor. As you can see, the diagonal of this parallelogram is the hypotenuse of a right triangle of with sides I_R and $I_L - I_c$:

$$I_t = \sqrt{I_R^2 + (I_L - I_c)^2}$$

Substituting our other values, we get:

$$I_t = \sqrt{8^2 + (4 - 2)^2}$$

$$= \sqrt{64 + 4}$$

$$= \sqrt{68}$$

$$I_t = 8.25 \text{ amperes}$$

The graph in figure 2-35 shows the current phase relationships. Notice that the $I_L - I_c$ curve is in phase with the IL curve, meaning that the circuit is inductive.

Of course, there are circuits with resistance, capacitance, and inductance where the current through the capacitance is greater than the current through the inductance. This shifts the parallelogram above the voltage vector. (In fig.2-35, it was below.) In finding total current, it makes no difference whether inductive or capacitive current is larger, for the square of a negative number is positive.

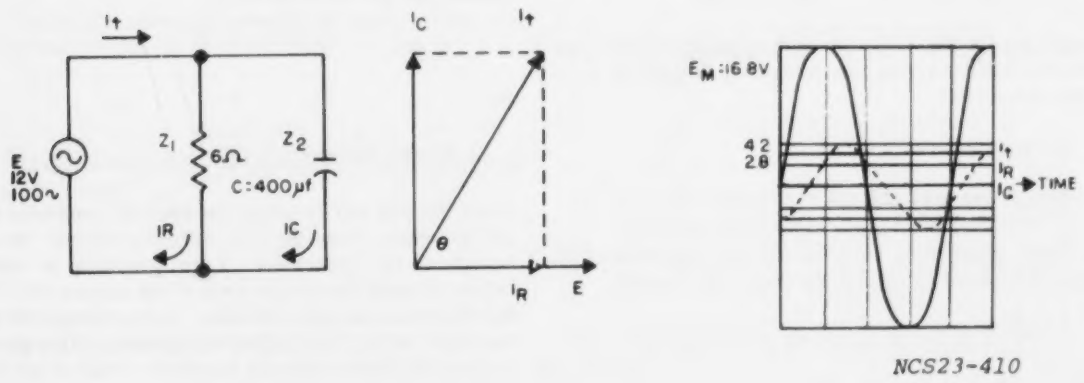


Figure 2–34. Parallel resistive-capacitive circuit.

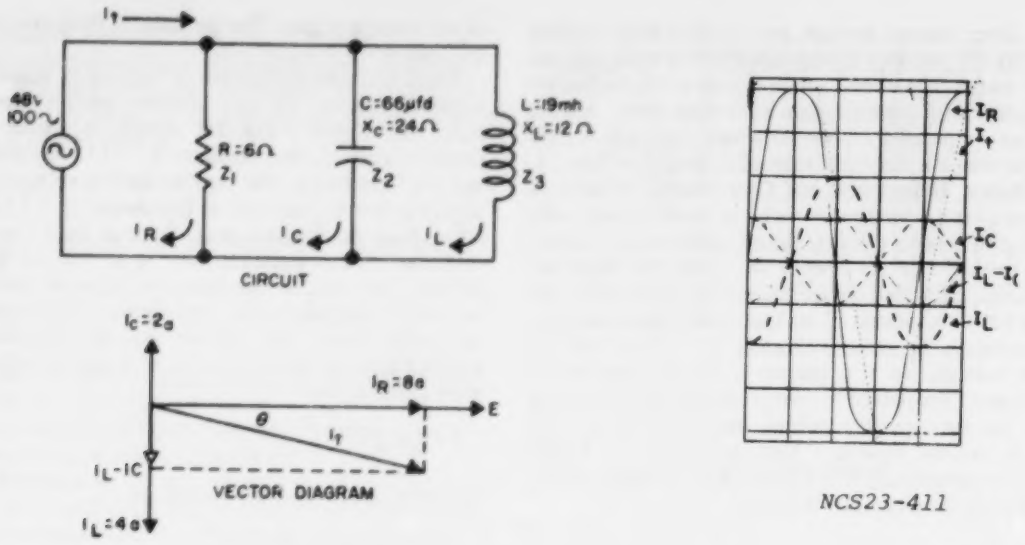


Figure 2-35. Inductive-capacitive circuit.

a. Phase angle: To find the phase angle θ, we substitute our I_R and I_t values in the cos θ equation:

$$\cos \theta = \frac{I_R}{I_t}$$

$$\cos \theta = \frac{8.00}{8.25} = 0.9697$$

For trigonometric tables:

$$\theta = 14°$$

b. Power: We find the true power consumed in the circuit by multiplying the product of applied voltage and total current by the power factor:

$$P = EI\cos \theta$$

$$\text{True power} = 48 \times 8.25 \times 0.9697 = 384 \text{ watts}$$

A simple way to check this answer is to multiply the voltage across the resistor by the current flowing through it, as in the power formula:

$$P = EI_R$$

$$P \text{ (true)} = 48 \times 8 = 384 \text{ watts}$$

c. Total impedance: To solve for total impedance, we plug our calculated values into the Ohm's law formula:

$$Z_t = \frac{E}{I_t}$$

$$Z_t = \frac{48}{8.25} = 5.82 \text{ ohms}$$

The vector shows the total impedance largely resistive, but since there's some inductive reactance, the current slightly lags the voltage.

Parallel Resonance. A parallel-resonant circuit is one of the most widely used devices in electronic receivers, transmitters, and frequency-measuring devices. Unlike a series-resonant circuit, it's characterized by high impedance and minimum line current at resonance. An important consideration in studying parallel resonance is the circuit condition that produces resonance. There are three different definitions of a tank circuit's resonant frequency (fig. 2-36): (1) the frequency of E_g at which I_t is in phase with E_g (unity power factor), (2) the frequency of E_g at which X_L equals X_c, and (3) the frequency of E_g at which tank impedance is minimum. These definitions lead to resonant frequencies that differ by as little as 1 percent when the circuit Q is large. For all practical purposes, the resonant frequency of a parallel circuit is the one that satisfies the second relationship:

$$X_L = X_c$$

or:

$$\text{Resonant frequency} = \frac{1}{2\pi\sqrt{26}}$$

Since the coil and the capacitor are both connected across the generator, there are two paths for current; the coil's branch or the capacitor's. If the generator is operating below resonant frequency, most of the current will flow in the inductive branch, because at low frequencies coil reactance is less than that of the capacitor. If the generator is operating above resonant frequency, most of the current will flow in the capacitive branch, since the capacitor's resistance is less at high frequencies less than that of the

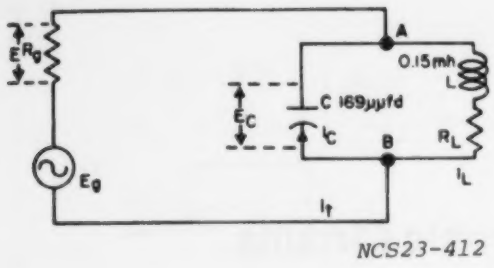


Figure 2–36. Parallel-resonant circuit.

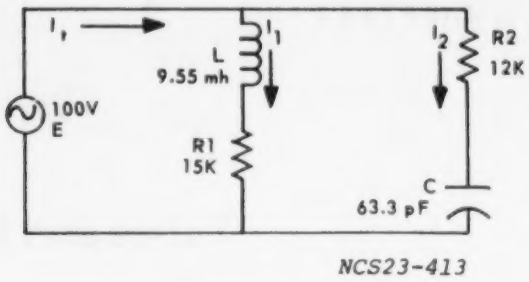


Figure 2–37. RCL circuit.

coil. Between these two extremes there's the resonant frequency, where the lagging inductive current and the leading capacitive current are substantially equal and, being nearly 180° out of phase, nearly cancel each other. The total, or line, current is then quite small, and the circuit impedance is correspondingly large. The circuit impedance at resonance is much greater than either inductive or capacitive impedance, and it's one of the most valuable properties of a parallel-resonant circuit. Since the parallel-resonant circuit offers a very high impedance to the current generated at the resonant frequency, it is often used for rejecting undesired frequencies.

Series-Parallel Circuits. Series-parallel circuits take many forms, some quite complex. Figure 2-37 shows a series-parallel AC circuit, in which two series circuits are connected in parallel. We solve the circuit by finding X_L and X_c (the frequency of the applied voltage must be known), then finding the impedances of each of the two branches (after finding the phase angle), and then solving for total impedance with the equation for solving two parallel branches (being sure to include the phase angles). When we know the total impedance, we can find total current and the current through each branch. When we know the branch currents, we can find the voltage drop across each individual impedance.

Exercises (215):

1. What is the phase relationship between voltage and current in a purely resistive circuit?

2. What's the term for total opposition to current flow in an AC circuit?

3. What determines whether a circuit will act capacitively or inductively?

4. What effect does frequency have on X_c and X_L?

5. When is a series circuit at resonance?

6. What do we call a circuit that's above resonance?

7. How do we find the Q in a circuit?

8. What happens to the phase relationship of current and voltage as they are applied to (a) a resistive circuit and (b) a capacitive circuit?

9. What is the phase relation of current to the applied voltage in a resistive branch?

10. What are the characteristics of a parallel-resonant circuit?

11. Will the capacitor or the coil have more current flow when the circuit frequency is below resonance?

12. What must we know to find X_L and X_C?

CHAPTER 3

Tubes and Electronic Circuits

ELECTRONIC equipment is composed of three basic types of electrical circuits—series, parallel, and series-parallel. Within the equipment we find that those circuits, and their associated components, function as rectifier circuits, amplifier circuits, or oscillator circuits. Basic examples of those circuits are shown in figure 3-1. those circuits are shown in figure 1-1.

As we break those circuits down to individual components, we find that they are composed of resistors, capacitors, coils, transformers, and switches. Those individual components are generally used in conjunction with electron tubes or transistors. In this section, our study concentrates on vacuum-tube circuits and component functions within those circuit, but you should keep in mind that transistor circuits can—and do—perform the same functions.

3-1. Vacuum Tube Rectifiers

A diode is used as a rectifier because it passes current in only one direction—from cathode to plate. Current does not flow from the plate to the cathode, and the plate does not emit electrons, but the plate will attract electrons from either the cathode or space charge when it is positive. Our study begins with the half-wave rectifier and progress through some of the commonly used rectifier circuits found in the Air Force equipment of today.

216. Specify the operational characteristics, use, or conditions of specific rectifier circuits from given schematic diagrams.

Half-Wave. A half-wave rectifer changes alternating current into pulsating direct current by permitting current to flow only during one-half of each cycle. When the plate becomes negative with respect to the cathode, electrons are repelled and no current flows in the tube. A single diode may be used as a half-wave rectifier because electrons flow in the tube only during the half-cycle when the plate is positive.

Figure 3-2 shows a simple half-wave rectifier circuit. The primary winding of the transformer is connected to an alternating current (AC) input source. The transformer is a step-up transformer that increases the 115-VAC input voltage to a higher value in the secondary. The small winding at the top of the transformer steps the voltage down from 115 VAC to a voltage level suitable for the filament voltage of the tube. The connections are indicated by the symbol xx.

One end of the high-voltage secondary winding is connected to the plate and the other end of the winding is connected to a junction of ground and the load resistance, R. The load resistor is connected to the cathode and is in series with the tube. The operation of the circuit is illustrated by the waveforms of the figure 3-2. The alternations of the input voltage, e_1, are reproduced by the transformer with an increase in voltage, e_2, in the secondary winding. The waveforms indicate a 180° difference in phase between e_1 and e_2. This difference is characteristic of induced voltages. The induced secondary voltage, e_2, is impressed across the diode and its series load resistance. The voltage causes current (i) to flow through the diode and its series resistor on the positive half-cycle (when the plate is positive). The resultant output voltage, e_3, across the load has a pulsating waveform called a ripple voltage.

When point 2 is positive and point 1 is negative, electrons flow from the ground junction point 1, through the load resistor R, to the cathode, to the

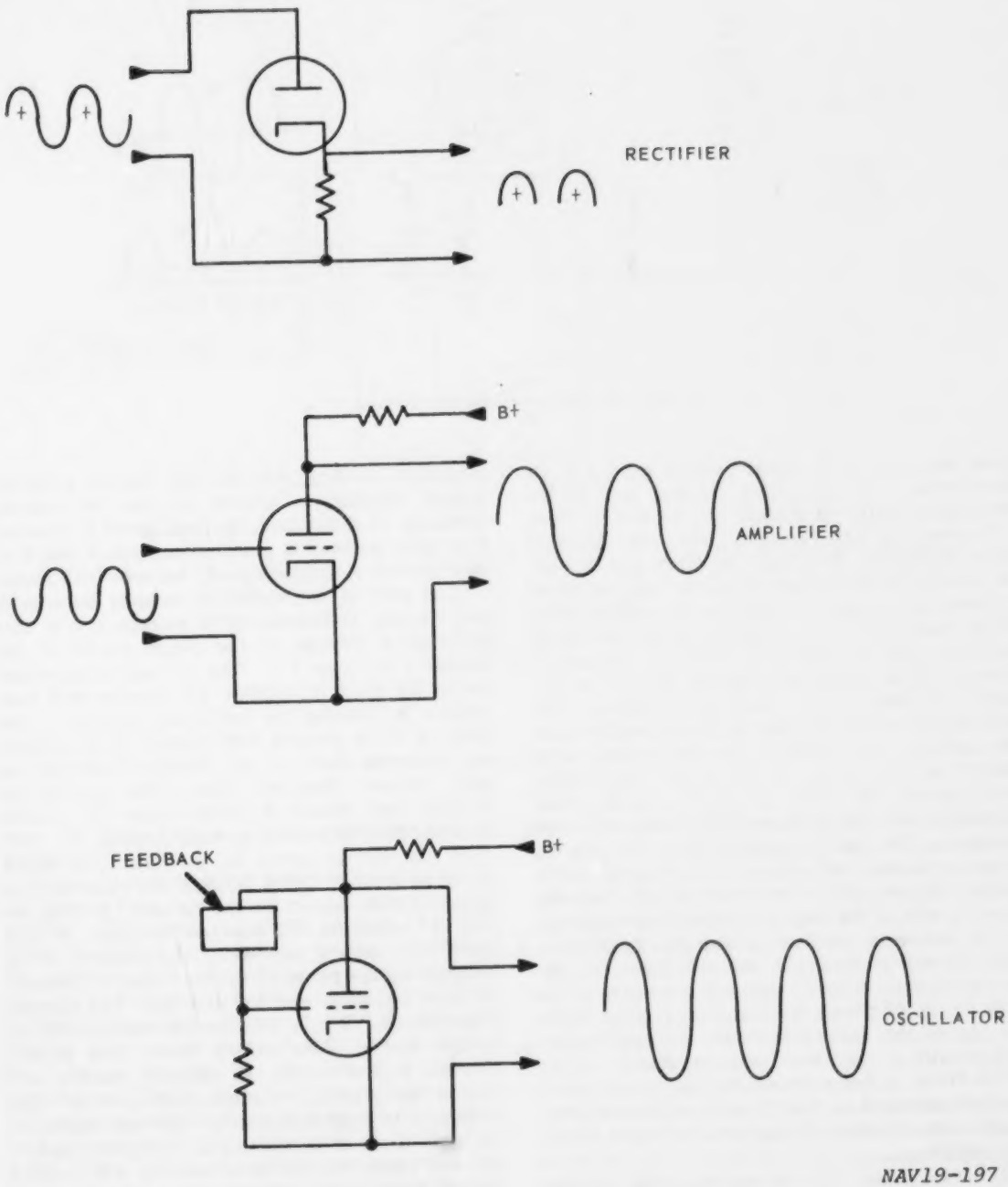


Figure 3–1. Basic electronic circuits.

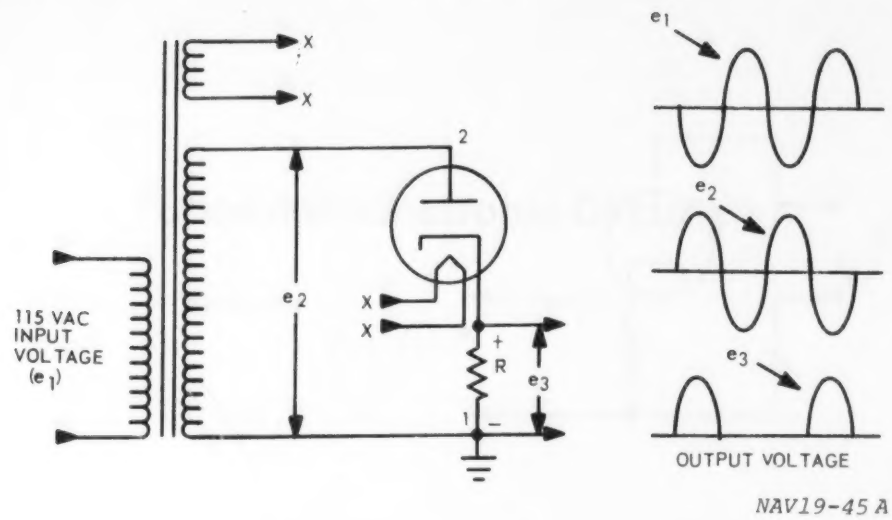


Figure 3–2. Half-wave rectifier and waveforms.

plate, and thus to the upper terminal point 2 of the transformer. The secondary winding acts as the immediate source of voltage for the current flow.

Because current flows in only one direction (point 1 to point 2) through the diode and its load, the polarity of the voltage across the load resistance is always as shown. The fact that the positive point of the load resistance is connected to the cathode of the tube may be confusing when the cathode is thought of as being the negative element of the tube. However, the only requirement for conduction is that the plate be more positive than the cathode. The cathode can be positive with respect to other points in the circuit. The voltage drop across the tube is usually small when compared with the voltage drop across the load resistance. The load is connected in the cathode circuit, as shown, rather than in the plate circuit to enable the use of a common ground for the negative side of the load and transformer winding.

The half-wave rectifier utilizes the transformer only one-half of the cycle, and less power can be developed than if the transformer were utilized on both halves of the cycle. This disadvantage limits the use of the half-wave rectifier to applications that require a very small current drain.

Full-Wave. A full-wave rectifier has two or more elements arranged so that the output current flows in the same direction during each half-cycle of the AC supply.

Full-wave rectification is accomplished by two diodes in the same envelope (a twin diode) with a common cathode connected to one end of the load resistance, as shown in figure 3-3. The other end of the load resistor is connected to the center tap, C, of the transformer secondary. Two halves of the secondary winding, AB and BC, may be a center-tapped winding, as shown, or may be separate windings. In either case, the load circuit is returned to a point midway in potential between A and B so load current is divided equally between both plates.

That part of the secondary winding between A and C may be considered a voltage source that produces a voltage of the shape shown at the circled 1 in figure 3-3. This voltage is impressed across the plate to cathode V1 in series with load resistor R. During the half-cycle, marked t_1, the plate of V1 is positive with respect to its cathode and electrons flow in the direction indicated by solid arrows. Electrons flow from ground up through load resistor R, which makes the cathode positive with respect to ground. During this half-cycle, the voltage across BC is negative, as shown at the circled 2 in figure 3-3, and the plate of V2 is negative with respect to the cathode. During the time V1 conducts, V2 does not conduct. A half-cycle later, during interval t_2, the polarity of the voltages on the plates of the two tubes is reversed. V2 now conducts, and V1 does not. The electron flow through V2 is in the direction indicated by the broken arrows. This current flows from ground through R and makes the cathode positive with respect to ground. Another half-cycle of load voltage is developed across R. Only one section of the twin diode is conducting at any given instant, but combined, the full-wave rectifier will conduct during 360° of the input cycle.

With two pulsations in the output for each applied cycle, the full-wave rectifier utilizes the power supply transformer for a greater percentage of the input cycle. This rectifier is more efficient than the half-cycle rectifier, has less ripple effect,

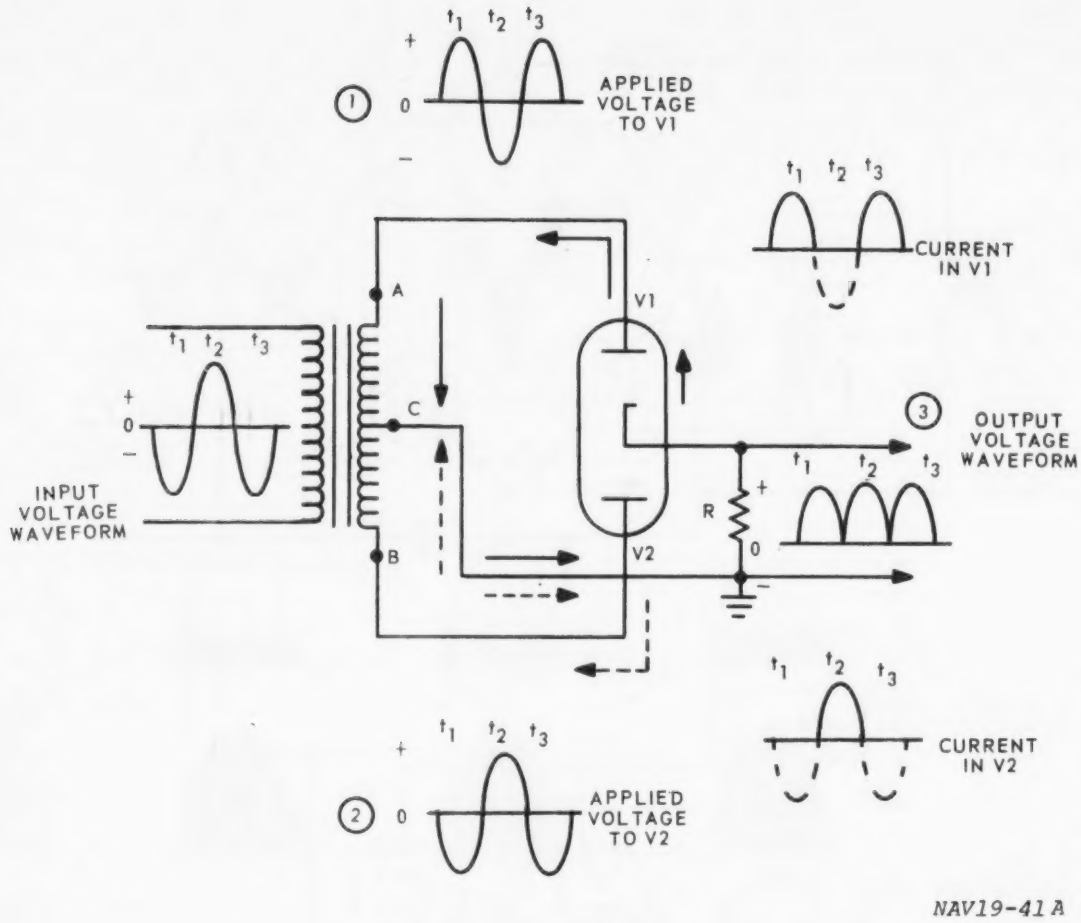


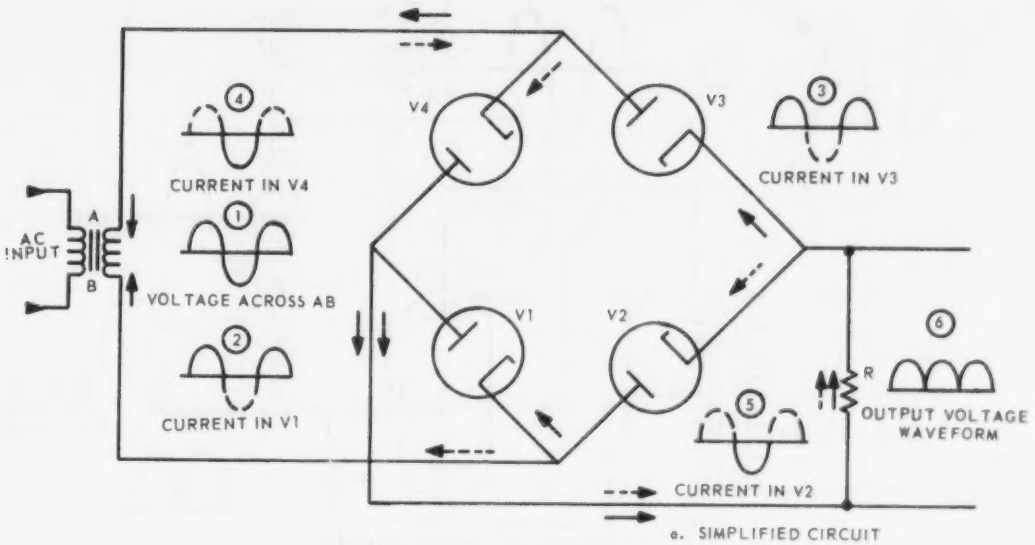
Figure 3–3. Full-wave rectifier and waveforms.

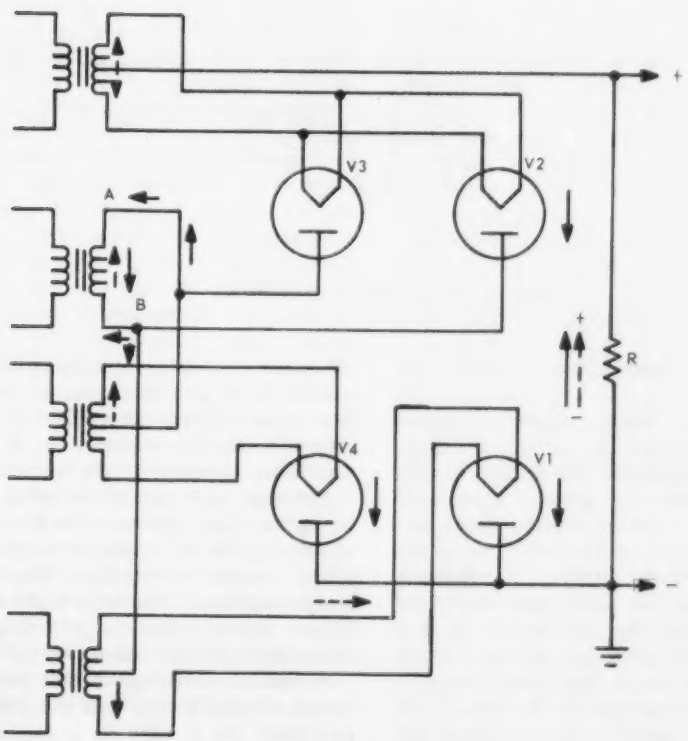
and is used for a much wider variety of applications.

Bridge. If four rectifiers are connected, as shown in figure 3-4,a, the circuit is called a bridge rectifier. The input (waveform circled 1) to the circuit is applied to diagonally opposite corners of the network, and the output is taken from the remaining two corners. During one-half cycle of the applied alternating voltage, point A becomes positive with respect to point B by the amount of the voltage induced in the secondary of the transformer. During this time, the voltage across AB may be considered to be impressed across a load consisting of V1, load resistor R, and V3 in series. When voltage is applied across the tubes, the plates become more positive than the cathodes. Electrons flow in a path as indicated by the solid arrows, and the waveform completes one-half cycle of the input; V1 and V3 are cut off and the same process is performed by V2 and V4 as the next half-cycle is fed in. The waveform for the V2 and V4 current is shown by the circled 4 and 5, while current flow path is shown by the broken arrows. Note that current through the resistive load is always in the same direction. The output voltage waveform appears at the circled 6.

Although only two of the tubes are conducting at any given time, current does flow for the full 360° of the applied AC signal. For this reason, the tube offers several advantages. One advantage of a bridge rectifier is that with a given transformer, the bridge circuit produces a voltage output nearly twice that of the full-wave circuits.

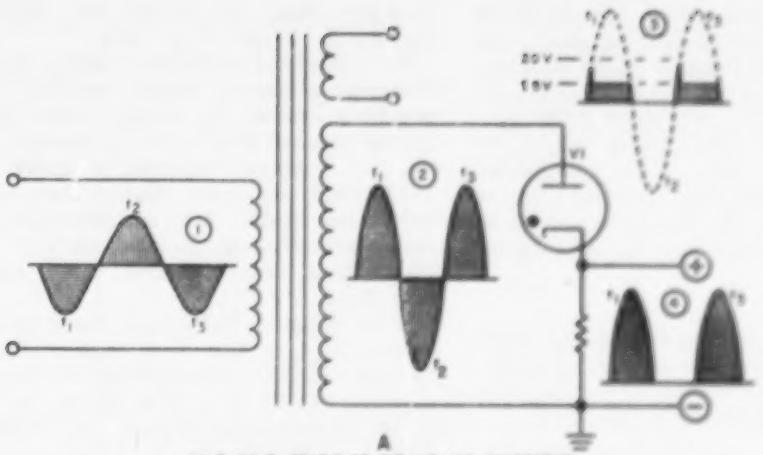
A second advantage is that peak inverse voltage across a tube is only half the peak inverse voltage impressed on a tube in a conventional full-wave rectifier that is designed for the same output voltage (1000 volts), the transformer secondary in the full-wave rectifier (fig. 3-3) has a 2000-volt peak developed across it, while that for the bridge rectifier (fig. 3-4,a) has only a 1000-volt peak. In this example, when V1 in figure 3-3 is not





NAV19-51

Figure 3–4. Bridge rectifier circuit.



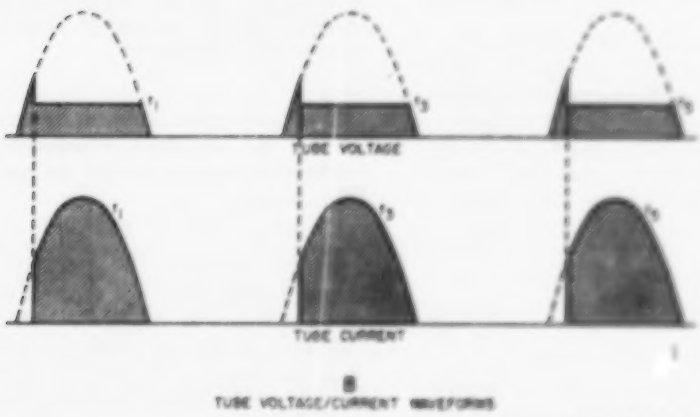


Figure 3-5. Gas tube half-wave rectifier and waveforms.

conducting, its plate is negative relative to its cathode by a maximum voltage of 2000 volts. The same is true for V2. This negative voltage is called the peak inverse voltage (PIV) and if greater than the maximum PIV rating of the tube, breakdown within the tube will occur. In figure 3-4,a, however, when tubes V1 and V3 or V2 and V4 are not conducting, the peak inverse voltage for any one tube is 1000 volts, which is half of the PIV across either tube in figure 3-3.

A disadvantage of this circuit is that three filament transformers are required for the tubes. In figure 3-4,b, the filament transformer connections of V2 and V3 are at the same relative potential and may be connected to the filament winding.

The filaments of V1 and V4 are returned to opposite ends of the high-voltage secondary of the power supply transformer and operate at the full potential difference that exists across the load.

Gas Regulators. Although a diode vacuum tube was used in explaining the rectifiers discussed thus far, substitution of other rectifier devices in this type of circuit will produce the same general results. Gas diodes can be used in the half-wave rectifier circuit where high circuit currents are required. As shown in figure 3-5, when the gas-filled diode functions as a rectifier, the circuit has several interesting characteristics. Note the voltage drop across the tube and the current through the load resistor. As the voltage applied to the anode increases from zero volts during interval t_1, for a small period of time there is no corresponding tube current. When the applied anode voltage reaches approximately 20 volts, the inert gas in the tube ionizes producing a heavy anode current through the tube and its load resistor, as shown for interval t_1 of waveform 4 in part A in part A of figure 3-5. (Part B of the figure shows the same information in

greater detail.) At the same instant, because of the heavy anode current through the gas diode, the voltage across the diode drops to about 15 volts, and it stays there for the remainder of interval t_1, as shown by waveform 3 in part A of figure 3-5.

The voltage across the load resistor will be the voltage across the secondary of the transformer winding minus the voltage that is dropped across the gas-filled diode, and the waveshape and phase appears as shown by 4 in part B, respectively.

Exercises (216):

1. The voltage applied to a rectifier circuit is 200 volts peak. Which circuit configuration produces two DC voltage pulsations for each input cycle at approximately 200 volts?

2. Using figure 3-4, specify when V1 will conduct.

3. With an input voltage of 250V peak AC applied at the secondary of all circuits illustrated in figures 3-2, 3-3, and 3-4, which will provide one 250-volt pulse for each cycle?

4. Where would gas regulator rectifiers be used?

5. What condition must exist for the tube in a half-wave rectifier to conduct?

6. How does the full-wave rectifier compare with half-wave rectifier as to efficiency and use?

7. In the bridge-type rectifier, how many of the tubes are conducting at a given time?

3-2. Filter Circuits

All electronic equipment consists of a combination of individual circuits, each of which is dependent upon particular values of voltages and current for their proper operation. To insure such a condition, it is often necessary to separate direct currents from alternating currents or alternating currents of a specific range of frequencies from alternating currents outside the desired range of frequency band. A device that performs this function is known as a filter.

For amplifiers, oscillators, modulators, and other electronic devices to operate properly, they must provide a smooth DC voltage source. A pure DC voltage supplied by a battery is desirable. However, the DC voltages required in many electronic applications are much higher than a practical battery can supply. Thus, a combination of rectifier circuit and filter circuit is necessary to produce a DC voltage of the desired value, and relative smoothness.

If the pulsating DC voltage that is present at the output of a rectifier were applied directly to a vacuum tube, the pulsations would cause improper operation of the tube. To suppress the magnitude of the variations in voltage, the rectifier output voltage is first applied to a filter circuit where various combinations of inductors, capacitors, and resistors produce the desired degree of ripple suppression. In the following discussion, ripple voltage and the action of various types of filter circuits are discussed.

217. Identify given filter network configurations, the effect of varying components within the configurations, and specify the application of given filter circuits.

Ripple Voltage. The polarity of a rectifier's output voltage does not reverse, but its magnitude varies above and below an average value as the successive pulses of energy are delivered to the load. In figure 3-6,A, average voltage is shown as the line that divides shaded areas A and B, and average voltage (E_{AV}) is equal to .636 times peak voltage (E_{PEAK}).

Fluctuations above and below the average voltage level are called ripples. Ripple frequency of a rectifier's output voltage is determined by the rectifier configuration and the frequency of the line voltage. In single-phase systems, the ripple frequency of a half-wave rectifier equals the line frequency. In full-wave and bridge configurations, ripple frequency is twice the line frequency, as shown in figure 3-6,B. Since both X_L (inductive reactance) and X_C (capacitive reactance) vary with frequency, ripple frequency plays a major role in determining the size of filter components.

The output voltage of any rectifier is composed of a DC component and an AC component. For most applications, the AC component (ripple voltage) must be reduced to a very low amplitude where the filter begins its work.

Capacitor Input Filter. When a resistor and capacitor are placed in parallel in the output of a half-wave rectifier, a change will be noted on the voltage appearing across the capacitor. Since C1 and R_L are in parallel, E_c is equal to ER_L and any

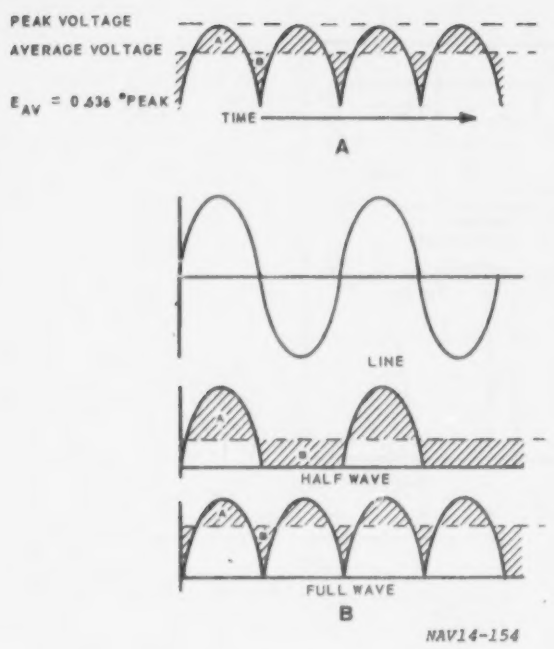


Figure 3-6. Unfiltered output.

variations in E_c will also appear across R_L, as shown in figure 3-7. Assuming that C1 has been charged to the peak input voltage, and that V1 is not conducting, C1 can discharge through R_L. The length of time that it takes C1 to discharge is determined by the size of C1 and R_L. The discharge time is expressed as a time constant. When the components are large, the time constant is long and E_c will decrease slowly. When the components are small, the time constant is short and E_c will decrease rapidly.

As the next positive pulse appears on the plate of V1, when the plate to ground voltage becomes greater than E_c, V1 again conducts, thus causing C1 to charge to peak input voltage. The process continues and waveform, as shown in figure 3-7,A, is produced. Notice that the average DC output is less than the peak input voltage, but greater than that which would exist without the addition of the capacitor in the filter. Again, the average DC voltage output would depend upon the value of the capacitor and the size of the load resistor. As the value of the filter capacitor or load resistor is increased, the average DC output voltage would increase because the RC time constant would be increased.

Figure 3-7,B, shows a full-wave rectifier having the same peak input voltage as the half-wave rectifier. The values of C1 and R_L have been kept the same; therefore, the time constant will remain the same. In the full-wave rectifier, there is less time between pulses fed to the filter, and E_C cannot decrease as much as it does in the half-wave circuit. This results in a higher average DC output voltage and a lower ripple amplitude. Since capacitor voltage E_c is higher at the time of tube conduction, the input pulse to the filter E_b remains lower and produces a lower peak plate current, I_b.

The effect of a decrease in the size of the load resistance is illustrated in figure 3-7,C. Since the analysis for both half-wave and full-wave circuits is essentially the same, only a full-wave circuit will be discussed.

Compare figure 3-7,C, with figure 3-7,B. The effects of decreasing R_L will cause the following effects. First, the time constant will become shorter. The shorter time constant allows capacitor voltage E_C to discharge to a lower level in the same amount of time. Another effect is that average DC voltage decreases and the amplitude of the ripple voltage increases. An additional effect is that since E_C has dropped to a lower value, plate current, I_b, increases.

Inductance Filter. An inductor may be used as a filter component because of its ability to store energy in the form of a magnetic field. An inductor resists changes in the magnitude of current flow, thus it is placed in series with the rectifier and the load rather than in parallel. The inductor used in rectifier filter circuits "chokes" or stops the passage of ripple voltage into the load, and is called a *filter choke.*

A common requirement of a rectifier and its associated filter circuit is that the regulation must be good; that is, the voltage must not rise greatly when the load is decreased or entirely removed. The regulation characteristics of a power supply with a choke-input filter can be improved by the use of a *swinging* choke. A swinging choke is a choke whose inductance varies in inverse proportion to the current flowing through it over the specified operating range. In any iron-core inductor, the inductance decreases very markedly as magnetic saturation is reached. In ordinary inductors, their magnetic saturation is just above the maximum current rating of the choke. In a swinging choke, this value is well above the maximum current rating.

A choke input filter, together with the input and output waveforms for both half-wave and full-wave rectifiers, is shown in figure 3-8. The half-wave input to and output waveforms from the filter are shown as parts A and B of the figure. Full-wave input and output waveforms to the filter are shown as parts C and D. E_{PEAK} is the maximum value of the waveforms; average value is shown as E_{AVG} which is the arithmetical average of all values in one alternation of a sine wave, which is .638 times peak, and E_{dc} represents.

As shown by the decreased amplitude of the waveforms, the choke offers a high impedance or

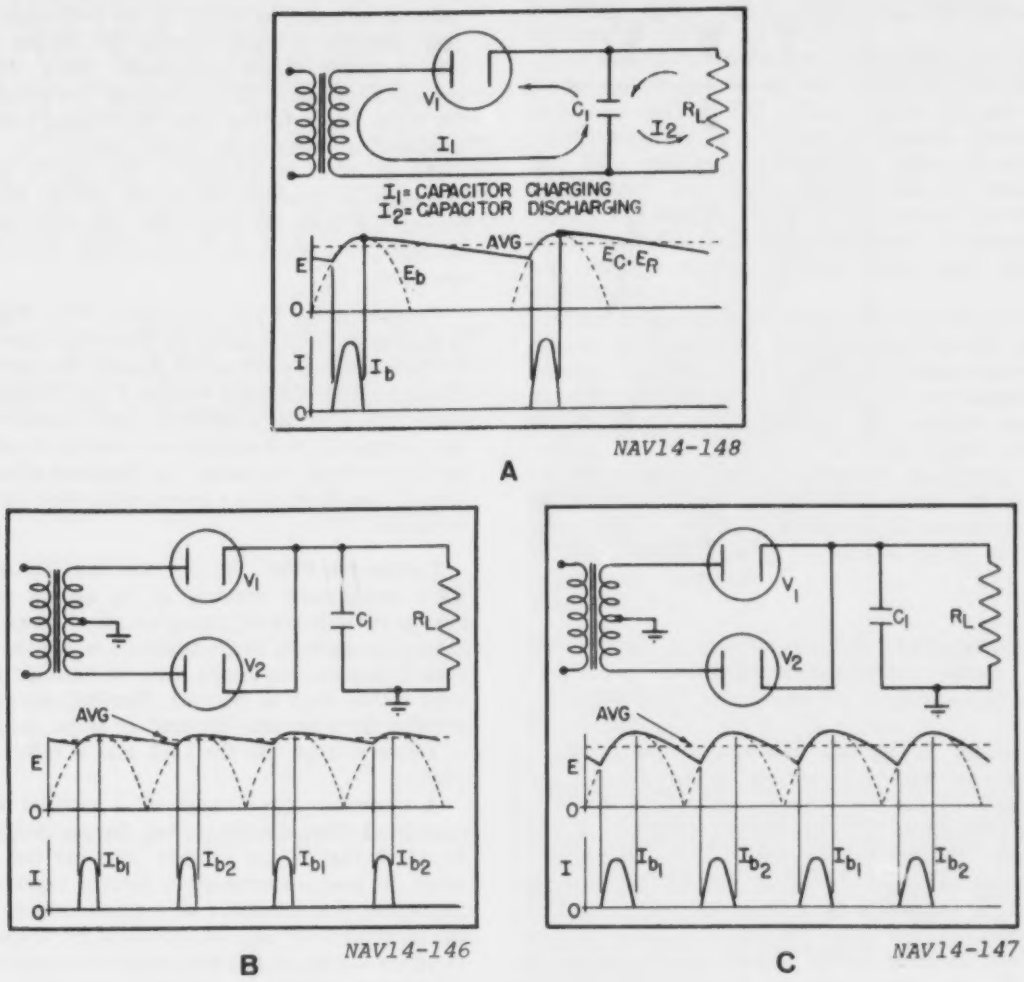


Figure 3–7. Capacitance filter and waveforms.

opposition to any change in current flowing through it. The filter input voltage increases from zero volts at the beginning of the input alternation, but the current builds up more slowly across the choke than in a capacitor-input filter circuit. The coil smooths out some of the ripple voltage by opposing any sudden changes in circuit current, and thereby acts to keep the current at a steady value when the output from the rectifier circuit begins to decrease. When the circuit current begins to decrease sufficiently, the magnetic field created previously by the increasing circuit current collapses, and the lines of force of the collapsing field cut the conductors of the choke, thus inducing a voltage that tends to keep the circuit current flowing at its former rate. During the times when the rectifier no longer conducts, circuit current due to the rectifier ceases to flow. However, the inductor still causes current to flow through the load resistor as long as the collapsing field exists. Hence, the use of a choke input filter prevents the current from increasing or decreasing too rapidly. If the inductance of the choke is sufficiently large, circuit current becomes nearly constant, and DC pulsations at the output of the rectifier do not reach the peak values that would be obtained without the inductance. Consequently, the output voltage never reaches the peak value E_{peak} of the applied voltage. A rectifier whose output is filtered by an inductor cannot produce as high a voltage as one whose output is filtered by a capacitor. This slight disadvantage is partially compensated for by the fact that the inductive filter permits a large current drain without a serious change in output voltage.

Unless the input choke contains a certain amount of inductance called the *critical value*, it tends to act as a capacitor input filter. When the choke has

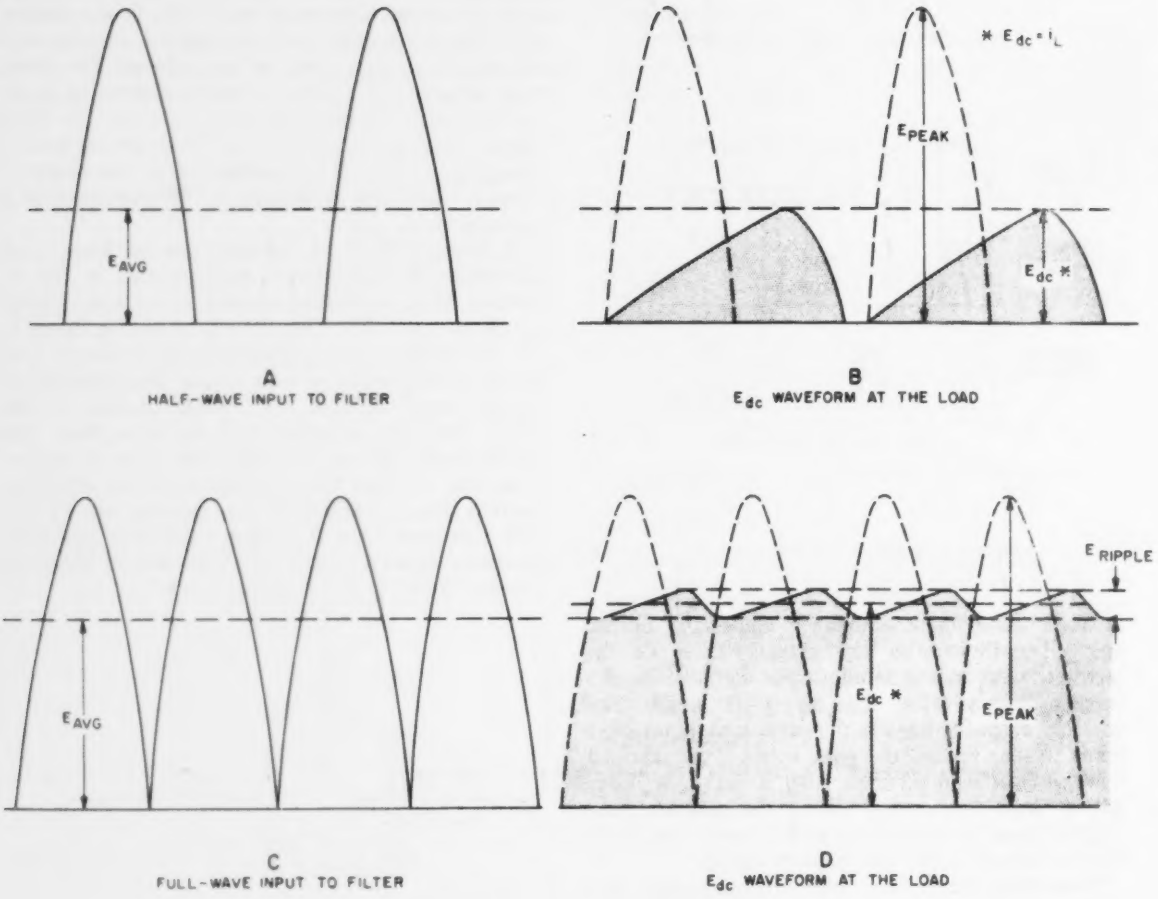


Figure 3–8. Inductance filter and waveforms.

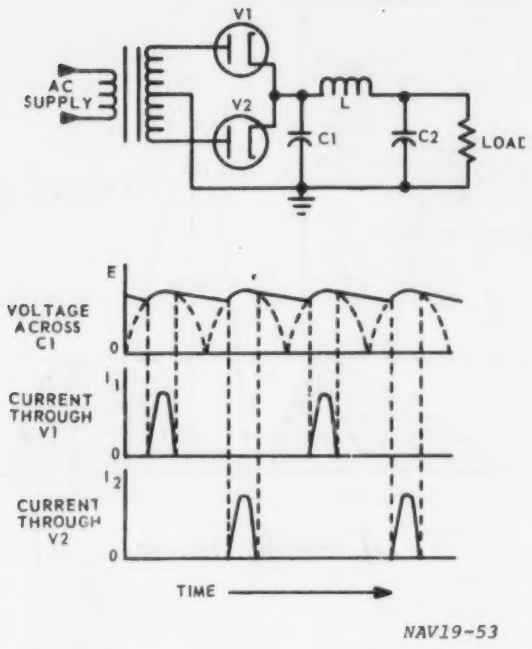


Figure 3–9. Pi-section filter and waveforms.

at least the critical inductance value, the output voltage is limited to the average value of the rectified wave at the input to the choke when the current drawn from the supply is small. The contrast output voltage in the capacative input filter tends to soar toward the peak value of the rectified wave at light load currents. Also, if the input choke has at least the critical value, the rectifier peak plate current is limited to about twice the direct current drawn from the power supply.

Pi-Section Filter. The ripple voltage present in a rectifier output cannot be eliminated adequately in many cases by either the simple capacitor or inductor filter. Filters are more effective if inductors and capacitors are used. The function of the capacitor is to prevent change in the magnitude of the voltage, while inductors simultaneously tend to prevent change in the magnitude of the current. This results in removing the ripple from the rectifier output and produces a voltage having nearly constant magnitude.

Figure 3-9 shows an inductance-capacitance filter used primarily with receiver power supplies and other low-current power supplies.

This type of filter is a "pi-section" because the schematic diagram resembles the Greek letter π. It is also called a capacitor input filter. With this filter, the output waveform approximates that of pure direct current. The input capacitor C1 will bypass the greatest portion of the ripple component to ground. In all filters, the major portion of the filtering action is accomplished in this first component. The series choke (inductor) maintains the current at a nearly constant level during charging and discharging cycles of the input capacitor.

Figure 3-9 displays waveforms of current through V1 and V2 and the voltage across C1. The final capacitor, C2, acts to bypass other fluctuations existing after filtering by the input capacitor and inductor. The current flow through the rectifier tubes is a series of sharp-peaked pulses, because the input capacitor acts like a short circuit across the rectifier while the capacitor is charging. Because of high-peaked pulses, the pi-section filter is used only in low current installations such as radio receivers.

L-Section Filter. A second type of filter, used primarily in high-current applications, is the L-section filter, so named because of its resemblance to an inverted "L." This filter is shown in figure 3-10. The components perform the same function as in the pi-section filter except that the inductor, or choke, input reduces the voltage output of the filter. This filter is called a *choke input filter*. The input choke allows a continuous flow of current from the rectifier tubes rather than the pulsating current flow demanded by the capacitor input filter. The L-section filter is seldom used with half-wave rectifiers because there is no device to maintain current flow between half-cycles.

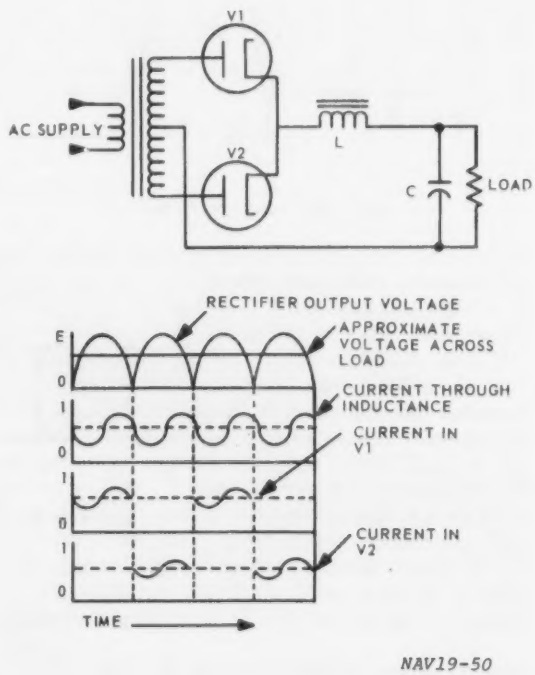


Figure 3–10. L-section filter and waveforms.

Because of the uniform flow of current, the L-section filter has applications in most high-power circuits where voltage regulation is important. Used with mercury-vapor rectifiers, its advantage is that it allows each rectifier tube to operate at a relatively constant level of current flow during its half-cycle of operation. This type operation allows a rectifier to supply the maximum current to the load. A disadvantage of the L-section filter is that instead of deliverying a voltage equal to the peak value of the transformer secondary, it supplies a voltage equal to the average of the AC voltage delivered to the rectifier. Two L-section filters are sometimes used in series to obtain a higher degree of filtering action.

Exercises (217):
Using the space provided below and figure 3-11, identify the diagram in the figure for the type filter listed in exercises 1 through 4.

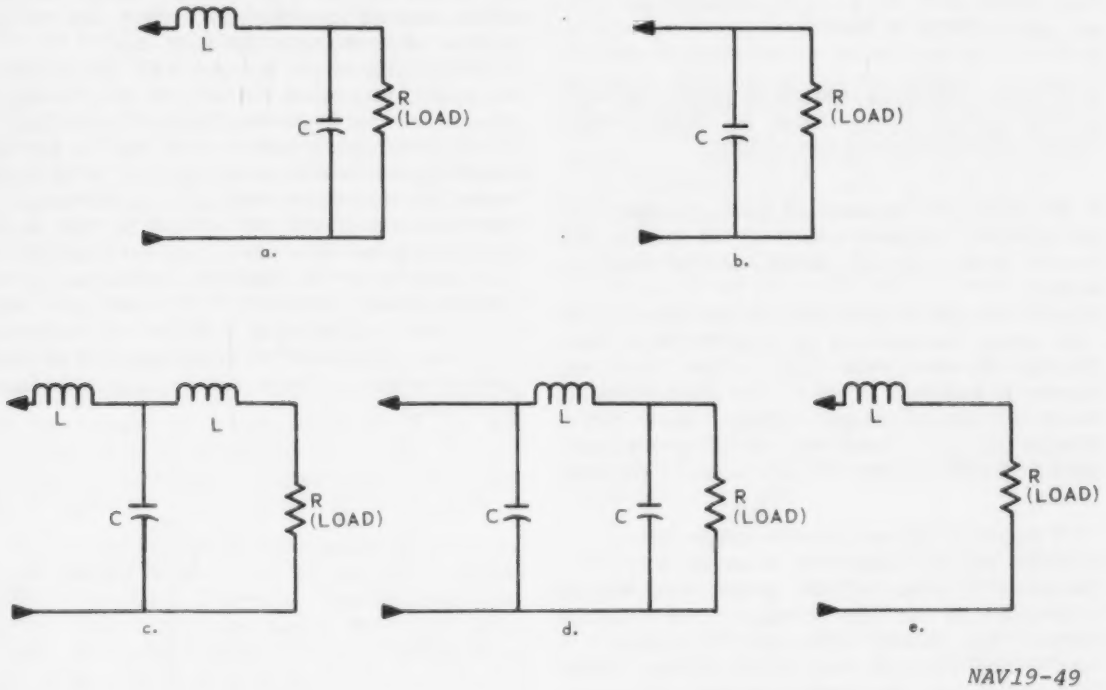


Figure 3-11. Objective 217, exercises 1 through 4.

1. Inductance-type filter _____ .

2. L-section-type filter _____ .

3. Pi-section filter _____ .

4. Capacitance-type filter _____ .

5. Where are pi-section filters used?

6. In the capacitor input filter, what happens to the time constant as the size of the components increases?

7. Where are inductive filters used?

3-3. Voltage Regulators

The output voltage developed by any source of power tends to decrease when current is drawn from the source. The amount of change in the output voltage is usually expressed as the *percentage of voltage regulation.*

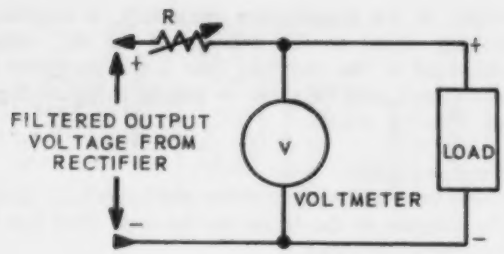


Figure 3–12. Simplified voltage regulator.

218. Given statements relating to voltage regulator circuit operational conditions or characteristics, identify the statements as true or false.

The difference between the no-load voltage and the full-load voltage is caused by the flow of load current through the internal resistance of the power supply.

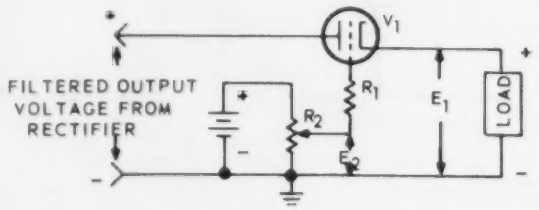
Most electronic gear will operate satisfactorily with certain variations in the supply voltage. Some circuits, however, are very critical and will encounter problems from a very slight deviation from the normal supply voltage. These circuits require the use of some type of voltage-regulating device. Generally, here is how a basic regulator works.

A regulator that stabilizes the output voltage of a rectifier usually takes the form of a variable resistance in series with the output. This variable resistance and the load resistance form a voltage divider. The variable component is controlled so that voltage across the load is held constant. Figure 3-12 shows a simple circuit that demonstrates this principle. The variable resistor, R, and the resistance of the load form a voltage divider connected across the rectifier output terminals. All the load current passes through R and develops a voltage. If the rectifier output voltage increases, the voltage across the load increases in proportion. To counteract the increase, the resistance of R is increased (manually) so that a greater proportion of the available voltage appears across R. The voltage across the load is held constant if the resistance of R is increased sufficiently to neutralize the increase of the rectifier output. If resistance of the load increases, a greater fraction of the available voltage appears across the load. Therefore, the resistance of R must be increased in order to hold the voltage across the load constant.

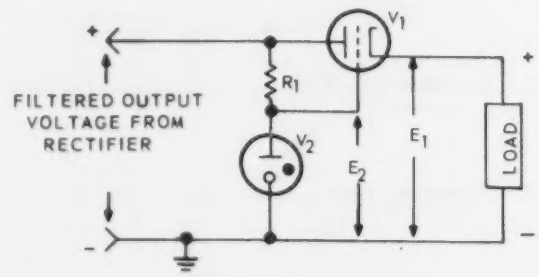
In the system shown in figure 3-12, the resistor, R, must be varied manually in order to keep the voltmeter reading constant. If the voltmeter reading increases, R must be increased. If the voltmeter reading decreases, R must be decreased. This same type of action must take place in all of the voltage regulators that are to be discussed, but the action is automatic. The more complicated circuits that follow are more desirable than the simpler circuits because they are more accurate and more responsive.

Triode Regulator. An electron tube may be considered as a variable resistance. When the tube is passing a direct current, this resistance is simply the plate-to-cathode voltage divided by the current through the tube and is called the DC plate resistance, R_P. For a given plate voltage, the value of R_P depends upon the tube current, and the tube current depends upon the grid bias.

The variable resistor in figure 3-12, can be replaced by an electron tube (shown in fig. 3-13,a) because the electron tube has a variable resistance. The resistance of V1 is established initially by the bias on the tube. Assuming the voltage across the load is the desired value, then the cathode is positive by some voltage, E_1, with respect to ground. The grid can be made positive relative to ground by a voltage, E_2, that is less than E_1. The potentiometer R2 is adjusted until the bias (grid-to-cathode voltage), which is $E_1 - E_2$, is sufficient to allow V1 to pass a current equal to the desired load current. With bias, resistance of V1 is established at the proper value to reduce the rectifier output voltage to the desired load voltage.



a. Fixed bias



b. Glow tube fixed bias

NAV14-125

Figure 3–13. Triode tube voltage regulator.

If the rectifier output voltage increases, the voltage at the cathode of V1 tends to increase. As E_1 increases, the negative bias on the tube increases and the plate resistance of the tube becomes greater. Consequently, the voltage drop across V1 increases with the rise in input voltage. The increased voltage drop across V1 is approximately equal to the increase in voltage at the input and the load voltage remains constant.

The resistor R1 is used to limit the grid current.

The voltage regulators shown in figure 3-13 compensate not only for changes in the output voltage from the rectifier but also for changes in the load. For example, in figure 3-13,b, if the load resistance decreases, the load current will increase. The load voltage will tend to fall because of the increased drop across V1. The decrease in load voltage is accompanied by a decrease in bias voltage on V1. The bias voltage on V1 is equal to $E_1 - E_2$. Thus, the effective resistance of V1 is reduced at the same time the load current is increased. The IR drop across V1 increases only a slight amount because R decreases about as much as I decreases. Therefore, the tendency for the load voltage to drop when the load is increased is checked by the decrease in resistance of the series triode.

Pentode Regulator. A more stable voltage regulator can be designed by taking advantage of the high amplification of a pentode (shown in fig. 3-14). It produces an output that is independent of fluctuations in the AC supply and changes in load over a wide range.

The output voltage of this regulator is developed across bleeder resistors R3, R4, and R5 in parallel with the resistance of the load. These resistors make up the resistance of one part of the total voltage divider. The other resistance, through which all of the load current must flow, is the cathode-to-plate effective resistance of V1. The other components of the circuit are used to control the resistance of V1 and maintain a constant voltage across the load.

The potential of the cathode of V2 is held at a constant positive value with respect to ground by the flow tube, V3. Current flowing from ground through V3 causes an IR drop across V3 that maintains the cathode of V2 positive with respect to ground. The grid voltage potential of V2 is selected by R4. This potentiometer is set so the grid-to-ground voltage is less positive than the cathode-to-ground voltage by an amount (the bias) that causes V2 to pass a certain plate current. The IR drop between the moving contact of R4 and ground is less than the IR drop across V3 by an amount that is equal to the bias on V2. The plate current of V2 flows through R1 and causes a voltage drop across it. The amount of the voltage across R1 is the bias on tube V1. The adjustment of R4 establishes the normal resistance of V1 and is used to set the value of load voltage the regulator must maintain.

If the load voltage tends to rise, whether from a decrease in load current or from an increase in the input voltage, the voltage between the moving contact on R4 and ground will increase. The difference in this voltage and the fixed voltage across V3 decreases. These voltages are in opposition, and the voltage between the moving contact on R4 and ground is less than the fixed voltage across V3. The grid bias of V2 decreases, and the plate current of V2 increases through R1. The increase in voltage across R1 increases the effective resistance of V1. If the load voltage tends to rise because of an increase in input voltage, this increase is accompanied by an increase in voltage across V1 and the rise in load voltage is checked. If the rise in load voltage is caused by a decrease in load current, this rise is checked by the IR drop across V1 remaining constant for the decrease in I is accompanied by an equal increase in R.

The anode of V3 is connected to the cathode of V2 and to the positive terminal of the regulated voltage output through R2. The glow tube is connected to the B+ in this way in order to cause the gas in the tube to ionize when the power supply is first turned on.

All the load current must pass through V1; therefore, this tube must be capable of passing a large current. In some regulators, a single tube does not have sufficient capacity to pass the required current and may require several identical tubes connected in parallel.

The type of regulator shown in figure 3-14 is widely used to stabilize the output voltage of rectifier power supplies. Because of excellent sensitivity to small changes of input voltage, this regulator is effective in removing ripple from the output of rectifier power supplies. The regulator serves also to filter the output of a rectifier, although the conventional filter systems usually are used in connection with a regulator.

Exercises (218):

Identify the following statements as being true or false.

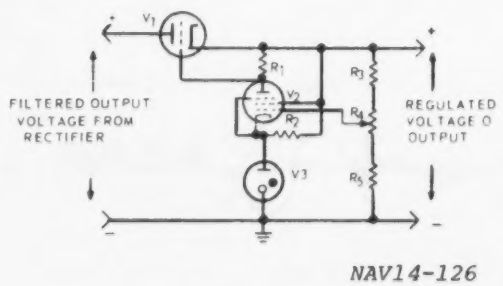


Figure 3-14. Improved voltage regulator.

_____1. The triode regulator circuit is widely used for stable outputs.

_____2. If the voltage output of the rectifier (fig. 3-13) decreases, the voltage on the cathode will decrease.

_____3. Bias change in the electron tube voltage regulator is a result of cathode potential change. (See fig. 3-13).

_____4. The major improvement in the improved voltage regulator (fig. 3-14) over the electron tube voltage regulator is the higher amplification of V2.

_____5. In figure 3-14, R3 established the initial operating bias of V2.

3-4. Power Supply

The electron tubes used in Air Force equipment require voltages of various values for their filament, grid, screen, and plate circuits. Power supplies furnish these voltages at the necessary current ratings. The problems involved in obtaining a suitable DC potential are as follows: (1) if the voltage is not sufficiently high, a step-up transformer must be provided; (2) voltage must be rectified; (3) ripples must be smoothed; and (4) some form of voltage regulation must be used.

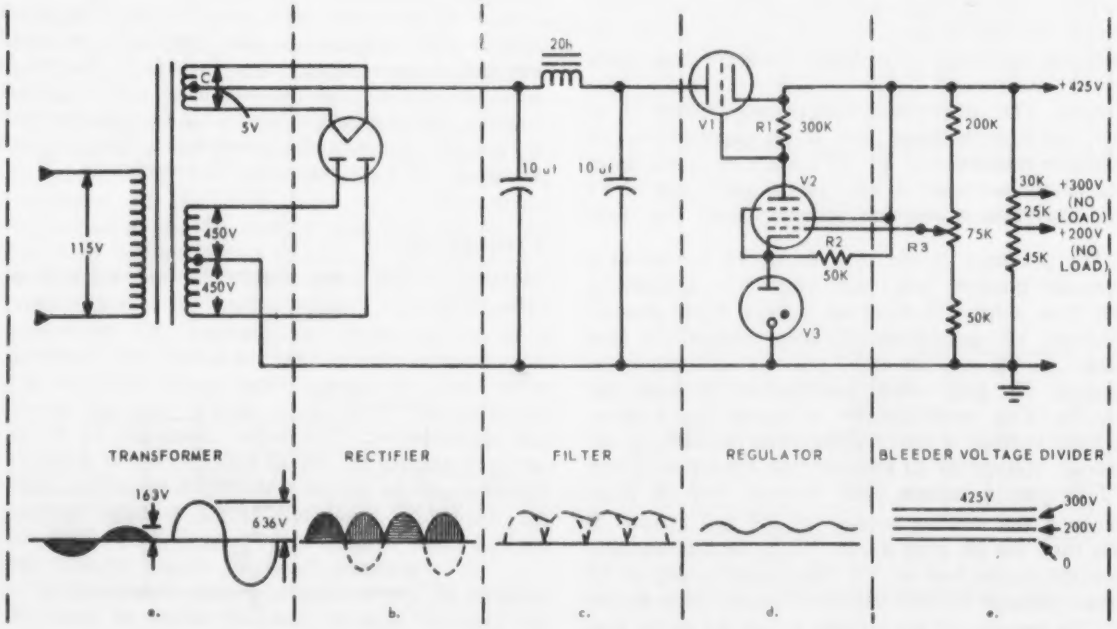
219. Select the correct response for given power supply operational characteristics.

Major Components. Figure 3-15 is a complete power supply showing a power transformer, full-wave rectifier, filter circuit, voltage regulator, and a voltage divider.

Transformer operation. Consider first the transformer (section a). Low voltage is stepped up by the transformer from 115 VAC to 900 VAC. The center tap provides a dividing point so that 450 VAC are applied to each section of the rectifier. The ends of the transformer alternately become positive and negative. Center tap, C, on the heater winding is used to force plate current to divide equally in each filament lead. If there is no center tap, a voltage divider of two equal resistors may be put across the secondary to produce the same effect. Alternately, positive and negative voltage is applied to the plates of the rectifier.

Rectifier operation (section b). The two plates conduct alternately as each plate is made positive by the secondary action of the transformer. Pulses of current flow from the filament line to each plate. The plates alternately become positive and negative with the applied AC, but the filament line will show a one-direction flow.

Filter operation. The capacitors charge when the rectifier conducts, and they discharge through the bleeder voltage divider when the tube is not conducting. The choke builds up a magnetic field when the tube draws current. The field collapses as current decreases, tending to keep a constant



NAV19-56A

Figure 3-15. Complete power supply.

current flowing in the same direction through the bleeder resistor and the load. The capacitor input (illustrated) gives higher voltage output with low current loads. The choke input gives steadier output will less ripple under load conditions.

Regulator operation. If the load draws more current or the AC input voltage falls, the terminal voltage of the power supply falls. Resistor R1, tube V2, and gas tube V3 are in series across the rectifier terminals. V3 holds the cathode of V2 at a constant positive potential with respect to ground, and setting of R3 determines bias on V2. A fall in terminal voltage causes more negative bias on V2, less current through V2 and, therefore, less current through R1. Less IR drop across R1 causes less negative bias on V1. V1 then acts as a lower value resistor, and terminal voltage decrease is checked.

Bleeder resistor. The bleeder resistor is a safety factor for discharging the capacitors when power is removed. It also acts as a load resistor to protect the voltage regulator at no-load, and improves regulation.

In addition, a voltage divider has taps placed at intervals for circuits that require voltages less than the maximum. The voltage divider is usually grounded at the lower end but may be grounded at any higher point to get a negative output.

Exercises (219):

1. To relate what effect a decrease in the transformer primary voltage from (1)15 VAC to 110 VAC would have on items 1 through (9) below, match the alternatives in column B to the items in column A. Some alternatives may be used more than once. (See fig. 3-15).

Column A	*Column B*
_____(1) The cathode potential of V2 with respect to ground.	a. More positive.
_____(2) The current through V2.	b. Less positive.
_____(3) Current through V3.	c. No change.
_____(4) The IR drop of V3.	d. Increase.
_____(5) The grid-to-cathode potential of V1.	e. Decrease.
_____(6) The IR drop across R2.	
_____(7) Current through V1.	
_____(8) The output voltage measured at the +200 VDC tap to ground.	
_____(9) Current through the bleeder resistor at the instant of primary voltage change.	

3-5. Basic Amplifiers

In 1907, when Lee DeForest invented the vacuum tube, he opened a new door to man's technical advancement. His device was a simple construction containing three active elements—a plate, a cathode, and a grid. Since the device contained three elements, DeForest called it a triode.

DeForest further discovered that by varying grid potential, he could control the plate potential and the amount of current flow; thus, he called the grid a "control grid." His experiment had proven that a small amount of electrical energy could control a much larger amount of energy. This process was called *amplification* and is similar to the action of an accelerator which is connected to a small valve in the carburetor of an automobile. It requires only a small amount of energy to operate the accelerator, yet the accelerator controls a vast amount of energy that operates the automobile.

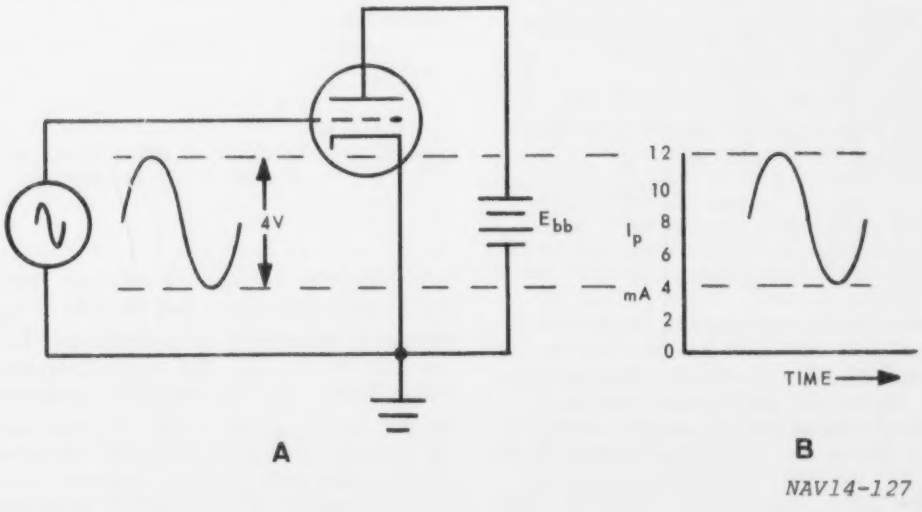


Figure 3-16. Triode amplifier and waveforms.

DeForest's invention has made possible further advancement in the field of electronics. In this section, you will see how modern variations of DeForest's invention are used in communications equipment.

220. Given parameters of an amplifier circuit, calculate operating characteristic values.

Signal Reproduction. As noted in the introduction, variations in grid voltage cause variations in plate current. In converting variations in plate current to voltage variations, the circuit provides voltage amplification. Figure 3-16 shows a simple triode tube performing that task.

In figure 3-16, we assume that E_{bb} is a constant voltage source that can have any amount of current drawn from it without causing a change in source voltage.

The 4-volt sine wave applied between the grid and cathode of the tube causes plate current to vary in a sinusoidal fashion, as shown in part B of figure 3-16. Since the input signal has a peak-to-peak amplitude of 4 volts, the grid reaches a potential of +2 volts at the peak of the positive alternation, and −2 volts at the peak of the negative alternation.

During the positive swing of the input signal, the plate current rises from its no-signal value of 8 mA to its peak positive value of 12 mA. Upon completion of the positive alternation, the grid becomes negative, causing plate current to decrease. At the peak of the negative alternation, the plate current decreases to its minimum value of 4 mA. Thus, as the grid completes one cycle of voltage, a similar sinusoidal variation occurs in plate current. Remember that we can draw any amount of current from the battery, E_{bb}, without causing a change in the plate voltage supplied. Our next step is to convert those changes in plate current into changes in plate voltage. We can do this by adding a plate load resistor (R_L) to the circuit.

Circuit Analysis. In figure 3-17, we have added a 10,000-ohm (10K) plate load resistor in series with the battery and the plate of the tube. Since this resistor is in series, it carries the total DC plate current. To explain the circuit, we are feeding a 4-volt peak-to-peak signal in on the grid, which we assume produces an 8-mA peak-to-peak change in plate current. With no signal applied, plate current is at the steady state of 8-mA.

Under the no-signal condition with 8 mA of current though the 10K ohm plate load resistor, the resistor will drop 80 volts (E = IR). Since our battery voltage source, E_{bb}, is 200 volts, the plate voltage, E_p, will be equal to the supply voltage minus the drop across the plate load resistor.

$$E_p = E_{bb} - E_{RL}$$
$$E_p = 200 - 80$$
$$E_p = 120 \text{ volts}$$

As the grid signal reaches its positive peak, the plate current will rise to 12 mA. At the positive peak of the grid signal, the plate voltage will be:

$$E_p = 200 - 120$$
$$E_p = 80 \text{ volts}$$

Notice that as the grid signal changes from 0 to +2 volts in the positive direction, the plate voltage falls from 120 to 80 volts. As the grid signal returns to 0 (completing the positive alternation), the plate current and plate voltage return to their original values of 8 mA and 120 volts respectively. Follow the grid signal through its negative alternation and make some calculations on your own. Then compare your calculations with the waveforms shown in part B of figure 3-17. Our next step is to determine the amplification factor or gain of the stage.

etu

Gain. To compute the amplification factor or gain, μ, of a stage, we consider the change in plate voltage to the change in grid voltage. When stated in mathematical terms, the symbol delta (Δ) represents change, E_p represents plate voltage, and E_g represents grid voltage. We show the mathematical formula, as follows:

$$\mu = \frac{\Delta E_p}{\Delta E_g}$$

Using the values of our circuit in figure 3-17, and the positive alternation, we have:

$$\mu = \frac{120 - 80}{0 + 2} = \frac{40}{2} = 20$$

Exercises (220):

1. Operating parameters of a circuit are: E_{bb} 400 volts, I_p 10 mA, R_L 20K. Calculate the values below for the no-signal condition.

   a. E_{RL}.

   b. E_p.

   c. I_{RL}.

2. Operating parameters of a circuit are: E_{bb} 300 volts, I_P 5 mA, E_{RL} 200 volts. Calculate the values below for the no-signal condition.
   a. E_p

   b. R_L

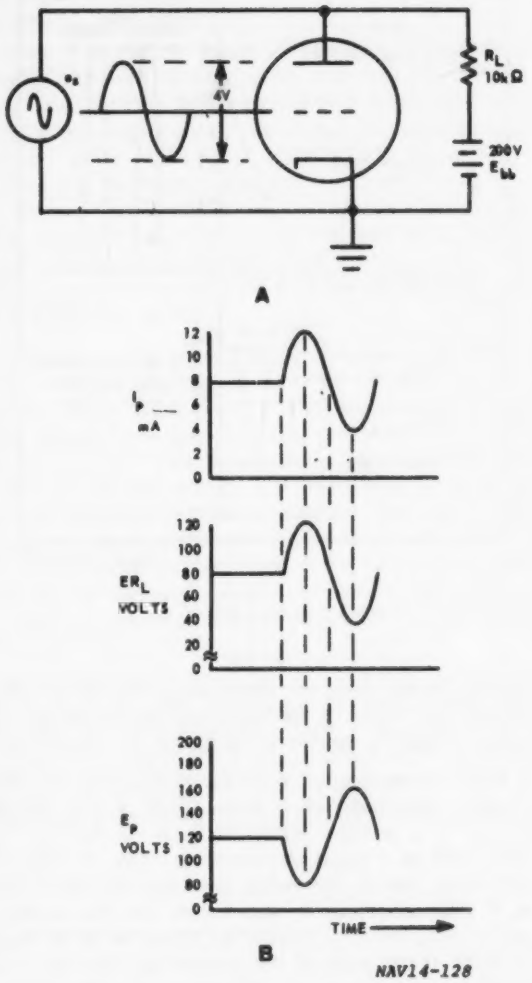


Figure 3–17. Triode amplifier and waveforms with RL.

3. If E_{bb} is held constant at 400 volts in exercise 1, and plate current I_p is increased to 20 mA, what happens to E_{RL}? Explain.

4. Calculate the μ of a circuit when plate voltage change is 80 volts and grid voltage change is 6 volts.

5. Assume that you had a grid signal of 8 volts peak-to-peak being fed in on the grid of the tubes in exercises 1 and 2; then calculate the amplification factor of both circuits if plate current increased to 15 milliamps in circuit 1 and to 6 milliamps in circuit 2.

a. μ of circuit 1

b. μ of circuit 2

3-6. Classification of Amplifiers

Amplifiers are categorized according to their use, type of bias, frequency response, circuit configuration, or resonant quality of the load. Our discussion is limited to classification by use, frequency range, and class of operation as determined by circuit configuration.

221. Identify amplifiers from given operational characteristics by completing statements that concern a particular type of amplifier.

Classification by Use. Amplifiers may be grouped by the way they are used in a circuit. Recall that in the previous section, we took a small voltage input and amplified it by a factor of 20. We also saw how varying component size made changes within the circuit. We can logically conclude that amplifier power gains are dependent on such factors as circuit configuration, size of the load resistor, and amount of input signal, and that amplifiers designed to produce large current gains are called current amplifiers, while amplifiers that produce large voltage gains are designated as voltage amplifiers. We will also see amplifiers designed specifically to deliver large amounts of output power (such as in the final stages of transmitters)—those are designated as power amplifiers or intermediate power amplifiers.

Classification by Frequency Response. Amplifiers may be designed to amplify either DC or AC voltage. The DC amplifier is one able to amplify one direct current voltage; that is, one in which the voltage and current do not vary. This type of amplifier is often found in oscilloscopes and computer circuits.

Audio frequency (AF) amplifiers operate in the approximate range of 30 to 15,000 Hertz although the audio frequency spectrum is considered to cover from 20 to 20,000 Hertz. These amplifiers use many different types of coupling between stages such as transformer coupling, impedance coupling, resistance coupling, and capacative coupling. Audio amplifiers are commonly used in the final stages of receiving equipment to produce the necessary power to drive speakers or headsets.

Intermediate-frequency (IF) and radio-frequency (RF) amplifiers both operate within RF frequency spectrum. Those amplifiers are commonly used in communication/navigation equipment to improve

the quality of signal by either increasing sensitivity or selectivity. These amplifiers are generally operated from 10 kHz to 300 GHz or higher, and are ordinarily designed for tuned circuit coupling for narrowband operation.

Video amplifiers are used extensively in television and radar systems. They are frequently called wideband amplifiers because they amplify a band of frequencies rather than a single signal. Operating range is usually in the 10-Hz to around 5-MHz range. Video amplifier circuitry closely resembles that of the audio amplifier except the coupling capacitor is usually larger, and the plate load resistor is usually smaller.

Classification by Class of Operation. The waveform of the signal voltage at the plate of a vacuum-tube amplifier depends on the waveform of the signal applied, and in part on the dynamic transfer characteristic that is used. In other words, the shape of the wave is dependent upon the amount of time that plate current is flowing as the grid signal is being applied to the tube. There are many classes of operation, and even subclasses of the main classes, but our discussion is limited to the most commonly used in Air Force equipment—class A, class B, class AB, and class C operations.

Class A operation. Class A amplifiers are biased in such a manner that as the input signal is fed to the control grid, plate current flows for the full 360° swing of the input signal voltage operating point of bias determining the amount of conduction.

In most applications of class A amplifiers, a distortion-free output is desired. To accomplish this, the bias is adjusted so that with no signal

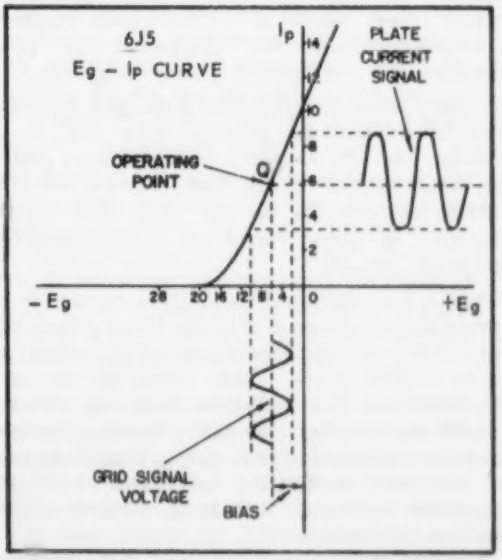


Figure 3–18. Class A operation.

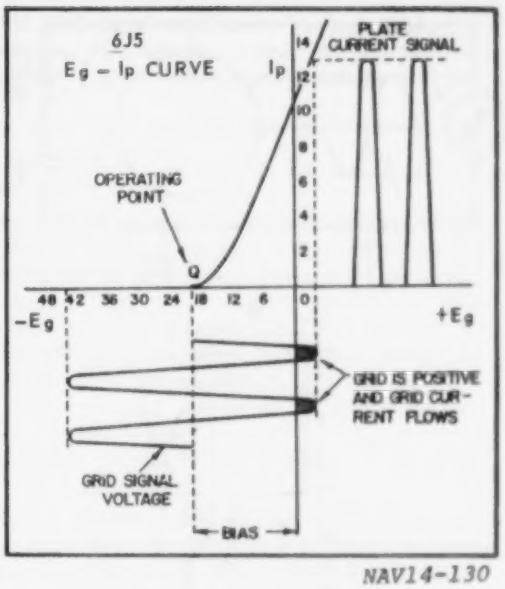


Figure 3–19. Class B operation.

applied to the grid, the operating point of the tube is near the center of the linear portion of the E_g - I_p curve, which is shown at point Q of figure 3-18.

Our sine wave applied on the grid figure 3-18 has a peak amplitude of 4 volts. That is, the signal swings in a positive direction from −6 volts to −2 volts and in a negative direction from −6 volts to −10 volts. The signal swing is commonly described as 4 volts above or 4 volts below the bias voltage point. Note that the total grid voltage swing is from −2 volts at the peak of the positive alternation to a peak of −10 volts on the negative alternation. Also note that as grid voltage is making its swing that the plate current swings above and below an average value of approximately 5.8 milliamps. If the E_g - I_p curve were perfectly linear, the increase in current on the positive alternation of the grid signal would be exactly equal to the decrease of current on the negative alternation, and the average DC plate current would be the same with or without a signal. In reality, the positive alternation of plate current is usually somewhat larger than the negative alternation, thus causing a slight increase in DC plate current as the signal is applied on the grid. This is a form of distortion caused by the curvature of the E_g - I_p curve and can usually be neglected when the tube is operated on the nearly linear section of the curve.

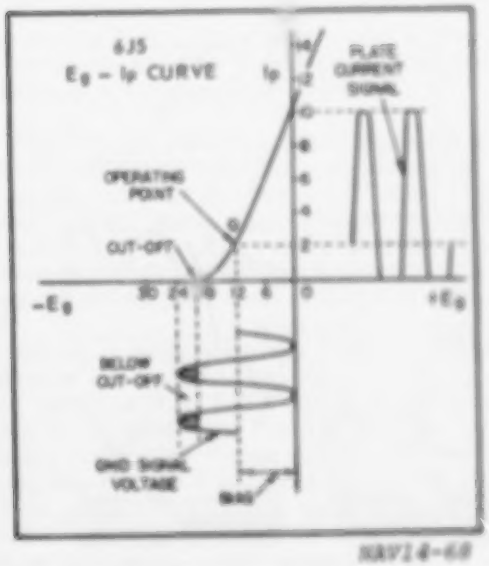
Class A amplifiers offer minimum distortion, low power output for a given tube (as compared to class B and class C amplifiers that we cover later), high-power amplification, and relatively low-plate efficiency. This type of amplifier is widely used in

Air Force equipment where low amounts of distortion are important

Class B operation. In class B operation, efficiency is greatly improved by shifting the operating point of the tube down the $E_g - I_p$ curve toward the cutoff point. The shift is accomplished by increasing the negative bias applied to the control grid, as shown in figure 3-19. Notice that the waveform output closely resembles that of the half-wave rectifier and that operating point Q is near the cutoff point at the −19-volt bias point. Power losses within the circuit are reduced because when no signal is applied on the grid, plate current is either zero or at a very low level.

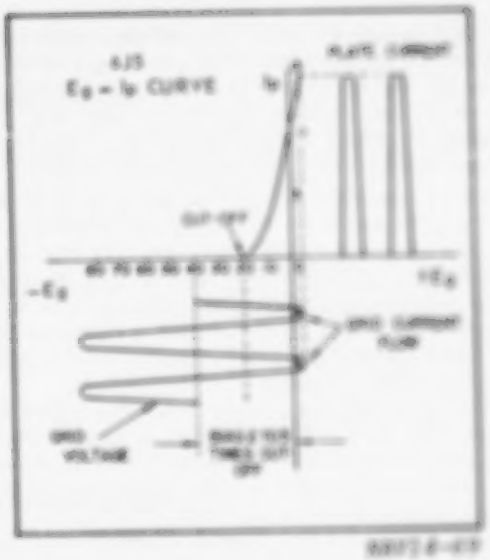
When a signal is applied to the grid, plate current will flow for approximately one-half (180°) of each cycle of the grid signal. Look closely at figure 3-19 and note that plate current flows only during the positive alternation of the grid signal. This is why the output resembles the half-wave rectifier output. This nonlinear operation of the tube produces harmonic distortion. Because of the distortion, single amplifier stages operated class B are unsuitable for audio amplification. However, when two class B amplifiers are combined in a single stage such as a push-pull amplifier, the majority of the distortion is eliminated.

Some characteristics of class B amplifiers are worthy of closer study. The grid signal is several times that required for class A operation of the same type tube. (NOTE: Compare the grid signals of figures 3-18 and 3-19, both of which use a 6J5 tube.) Distortion in class B operation is increased as the large input signal positive



NAVEDTRA 172-4-6-69

Figure 3-20. Class AB operation.



NAVEDTRA 172-4-6-69

Figure 3-21. Class C operation.

alternation goes to its positive peak (shown in the shaded area of fig. 3-19) and enters the positive grid voltage region of the curve.

In summary, you may characterize class B amplifier operation as having medium output power, medium plate efficiency (about 60 to 65 percent), large bias voltage, large driving signal requirements, and severe distortion when used as a single-tube audio amplifier. Remember, however, that two tubes can be connected in push-pull operation and operated class B with minimal distortion.

Class AB operation. Class AB operation has been deliberately delayed until now because it is a compromise between class A and class B operation. Class AB amplifiers have grid biases and input signal voltages of such values that plate current flows for appreciably more than half of the input cycle, but less than the entire cycle. Figure 3-20 shows such an amplifier with its input and output waveforms. In this class of operation, we have low distortion (characteristic of class A operation) and higher efficiency (characteristic of class B operation). Class AB operation is usually subclassed as AB_1 or AB_2.

If the input signal drives the grid positive with respect to the cathode, grid current will flow during the positive peaks and the amplifier is designated as a class AB_2 amplifier. Although the class AB_2 amplifier delivers slightly more power to its load than the class AB_1 amplifier, the class AB_1 amplifier has the advantage of presenting a constant impedance to its driver. In contrast with class AB_2, the AB_1 amplifier draws grid current over a portion of its input cycle which presents a

changing impedance to its driver at the point where grid current starts to flow. Thus, when grid current flows, the impedance falls to a relatively low value. The driver that supplies this kind of load must be designed to supply undistorted power to the load during these periodic intervals of low impedance.

Class C operation. Class C amplifiers have biases that range from two to five times the cutoff bias—consequently plate current flows for less than half (approximately 160° or less) of each cycle of the input signal. Because of the brief period during which the tube conducts, the average current is small compared to the peak plate currents and plate efficiency of 70 to 80 percent are easily obtainable.

Class C amplifiers are not used as audio amplifiers because they produce extreme distortion. They are used as RF power amplifiers in transmitters, however, where tank circuits can be used as plate loads to restore the missing portions of each cycle.

Figure 3-21 illustrates a class C amplifier. Note that the operating point is far below cutoff, and that the input grid signal must be large enough to drive the grid substantially positive at the crest of the positive alternation. In fact, we frequently find power amplifiers in which the control grid is driven from fifty to several hundred volts positive in RF transmitter stages of Air Force equipment.

Exercises (221):

Fill in the blanks of the following statements with information which best identifies that particular type of amplifier.

1. Audio-frequency (AF) amplifiers operate in the frequency range of _____ to _____ Hertz.
2. Intermediate frequency (IF) amplifiers operate in the frequency range of _____ to _____ or higher.
3. Video amplifiers operate in the frequency range of _____ to _____ .
4. In class A amplifiers, plate current flows for _____ of the input.
5. In class B amplifiers, plate current flows for _____ approximately _____ of the input signal.
6. Class C amplifiers are not used as audio amplifiers because _____ .
7. Amplifiers are classed by _____ , _____ , and _____ .

3-7. Distortion

A signal consisting of a single frequency is rare because the signal may originate from human voices, musical instruments, or other sound producers. Any of these sounds consist of *many* frequencies. If some of these frequencies are lost in the process of amplification, the reproduced sound will not be a faithful reproduction of the original signal. The failure of an amplifier to "reproduce" is called distortion. There are three types of distortion in amplifiers—frequency, amplitude (also called harmonic or nonlinear), and phase.

222. Select the cause of given amplifier distortion.

Figure 3-22 shows two signals that could appear on the grid of an amplifier. The top signal is the

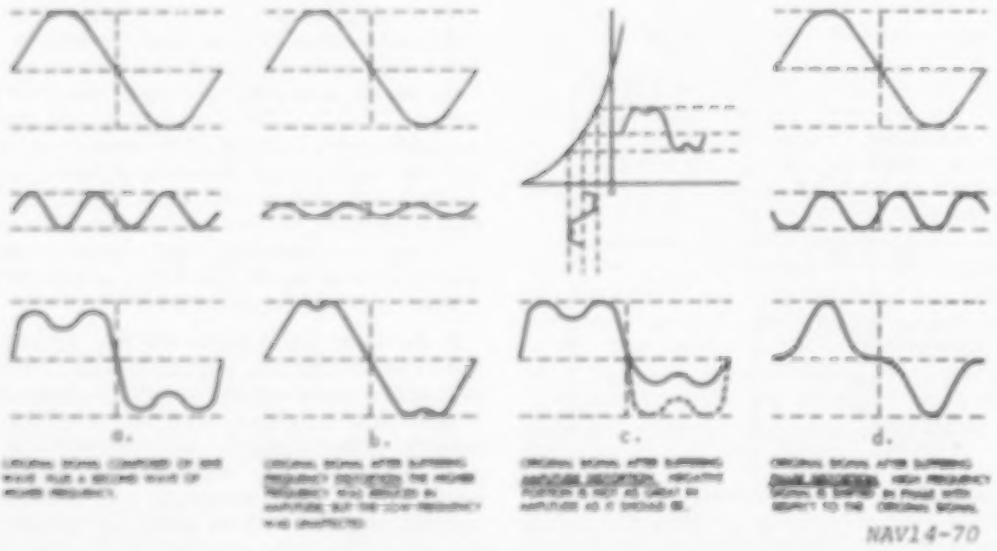


Figure 3-22. Amplifier distortion.

fundamental, the middle signal is the third harmonic, and the bottom waveshape is the sum of the two.

Frequency. Frequency distortion occurs when some frequency components of a complex signal are amplified more than others. For the most part, frequency distortion is caused by the variable reactance of C_c and C_s (C_c = coupling capacitance and C_s = interelectrode and stray wiring capacitance). Frequency distortion is kept to a minimum by insuring the bandwidth of the amplifier is wide enough to include all significant frequency components of the signal.

If both frequencies are not amplified the same amount, the resultant could be as shown in figure 3-22. This is *frequency distortion*. Frequency distortion is produced by applying a frequency to an amplifier that is above, or below, the frequency response of the amplifier. It is very important an amplifier be designed with ample consideration to the normal operating frequency of the circuit. This type of distortion is common in circuitry with a wide band of frequencies, such as a sound system.

Amplitude. Amplitude or "nonlinear" distortion occurs whenever the amplifier operates over a nonlinear section of its characteristic curve. Amplitude distortion can be caused by improper bias or too large an input signal. Severe amplitude distortion occurs if peak clipping occurs as a result of driving the tube into cutoff or to the point of grid current flow.

When one alternation of the output signal does not have the same amplitude as the other, *amplitude distortion* has occured. This is shown in figure 3-22. Amplitude distortion is caused by operating the amplifier on the nonlinear portion of its characteristic curve. This accounts for the term "nonlinear" distortion. Operating on the nonlinear portion of the curve will also produce harmonics, which is amplitude distortion.

Phase. Phase distortion exists when the plate relationships are not the same between the frequency components of the output signal and the input signal. Phase shifts occur because the amplifier becomes highly reactive at frequencies far above and below the midband frequencies. At these extreme frequencies, phase shifts become nearly 90°. Thus, if a complex waveform containing high-frequency, medium-frequency, and low-frequency elements are applied to the input of an amplifier, the mid-range frequencies will be amplified with little or no phase shift. The high frequency will be caused to lag its former phase, and the low-frequency signal will be caused to lead with respect to its original phase. Since the three signals have been shifted in time, relative to each other, they no longer produce the same complex waveform when added together in the output of the amplifier. Figure 3-22 shows the high-frequency component of the signal shifted 180°, producing a distorted output.

Exercises (222):

1. Select from column B the cause for the given amplifier distortions of column A.

Column A	*Column B*
_____(1) Frequency.	a. The reactances of an amplifier circuit result in high-frequency lag and low-frequency lead.
_____(2) Phase.	b. Amplifier gain has decreased 30 percent from maximum.
_____(3) Amplitude.	c. A change in amplifier bias has resulted in operation over the nonlinear portion of its characteristic curve.

3-8. Biasing Methods

The application of an alternating voltage between the grid and cathode of tube that causes variations in the plate current may also cause current to flow from cathode to grid during the positive half-cycle of the voltage. The grid current consumes power and tends to introduce distortion in the plate current waveform. It is desirable that the output voltage (which appears across the plate load resistor) is a faithful reproduction of the input (grid) voltages. The flow of grid current can be avoided by using a DC voltage between grid and cathode so that the grid is always more negative than the cathode. The voltage is called *bias*.

For example, if the alternating voltage has an effective value of 3 volts, its peak value will be 4.24 volts. Under these conditions, the placing of −7.5 VDC in series with the alternating voltage (between

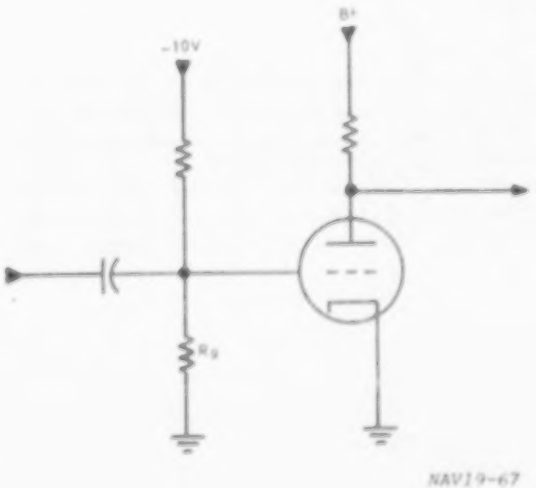


Figure 3-23. Fixed bias.

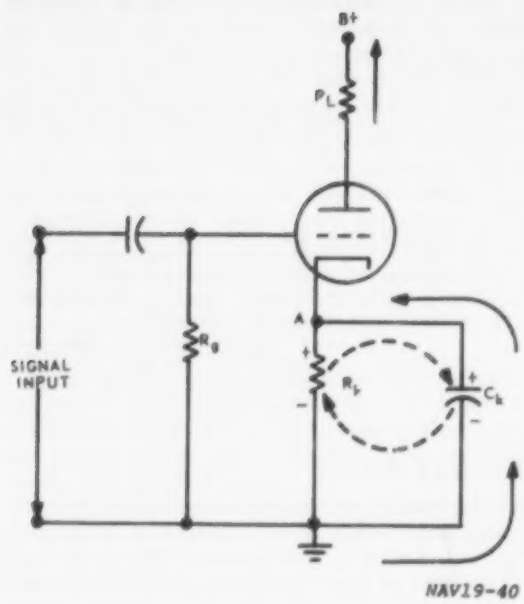


Figure 3-24. Self or cathode bias.

the grid and cathode) prevents the flow of grid current. The grid voltage will vary from negative 3.26 volts (−7.5V + 4.24V) to negative 11.74 volts (−7.5V − 4.24V). This voltage difference, called bias, is generally furnished in one of three different ways.

223. Identify types of bias for given electronic tube circuits.

The three common methods of biasing tubes are called *fixed, self* or *cathode bias,* and *grid-leak bias.*

Fixed. Fixed bias is supplied by voltage divider circuits, incorporated in radio and radar applications. Current flow through the voltage divider (fig. 3-23) causes a voltage drop across the resistor R_2, which makes the grid negative with respect to the cathode. Thus, the cathode at ground potential is positive with respect to the grid.

Self or Cathode. Self-bias is a term often applied to cathode bias, since it results from the plate current of the tube flowing through the cathode resistor (fig. 3-24). The tube conducts, producing a voltage across the cathode resistor. Current flows from ground, through R_k to the cathode, and through the tube of R_L to B+. Point A is positive with respect to ground. Since the grid is grounded, it is negative with reference to the cathode. (Since no current flows through the grid resistor, there is no voltage drop across it; therefore, both ends are at ground potential as long as no current flows in the grid resistor.) Under static conditions, the circuit continuously conducts unless a signal is applied.

With a signal applied, our story is different. A change in grid voltage produces a change in plate current, which alters the bias. For this reason, a large capacitor (C_k) called a bypass is placed across the cathode resistor to stabilize the bias when a signal is applied. The cathode bypass has a low reactance at the signal frequency and is usually selected to have a reactance that is not more than one-tenth of the value of R_k at the lowest frequency to be amplifier.

Grid Leak. Grid-leak bias, another form of self-bias, depends upon the input signal. Two circuits for obtaining this bias are shown in figures 3-25,a, and 3-25,b.

While the circuits appear different, they are similar in action. In figures 3-25,c, and 3-25,d, the plate and grid resistors have been omitted. With an input signal (e_i), the tube grid acts as the plate of a diode during the positive alternation, and C1 charges as indicated. This action is the same in each circuit. With C1 charged to the positive peak value of the signal, it will try to discharge as the voltage falls to zero and goes through its negative alternation. The discharge paths are shown in figures 3-25,e, and 3-25,f. While the cathode-to-grid resistance was small (about 2K ohms), permitting the capacitor to charge rapidly, the grid-leak resistor is large, making the discharge time much longer than the charge time. After a time of one cycle, the capacitor takes on an additional charge

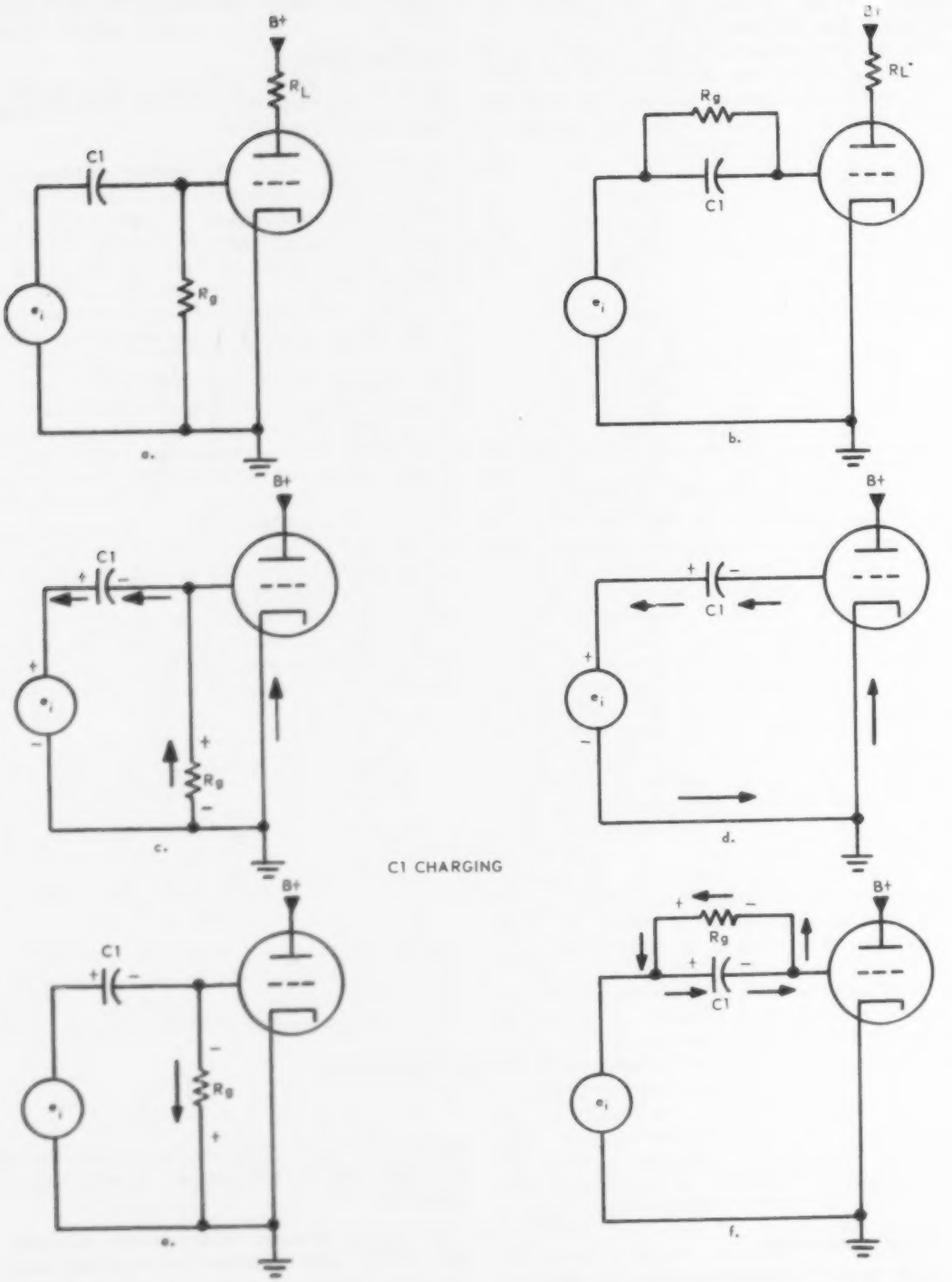


Figure 3–25. Grid-leak bias.

that is sufficient to make up for the discharge. In this way the voltage across R_g is kept fairly constant. This action is comparable to rectification and filtering.

With the grid connected to the negative end of the grid-leak resistor and the other end connected to the signal source, we see that in either case the signal voltage is in series with the bias voltage. In this way, the signal voltage is made to "ride" the bias voltage just as with fixed and self or cathode bias.

Exercises (223):

Identify the circuit in figure 3-26 which illustrates the bias methods listed below.

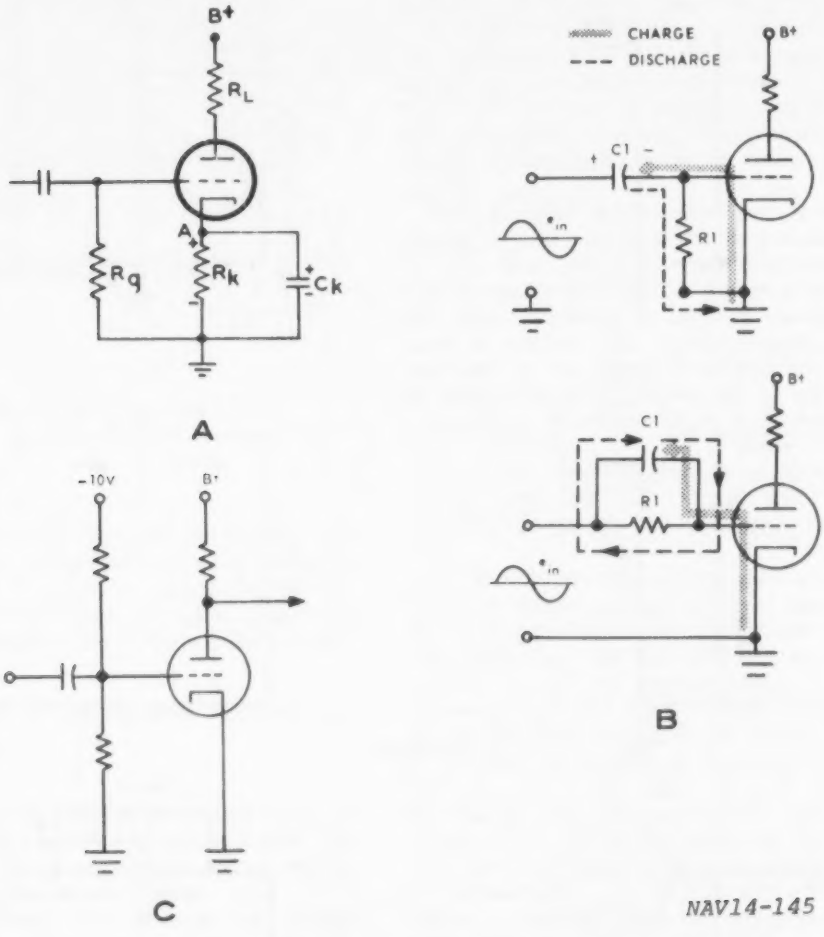


Figure 3-26. Objective 223, exercises 1, 2, and 3.

1. Fixed bias _____ .
2. Self- or cathode bias _____ .
3. Grid-leak bias _____ .

3-9. Coupling Methods

A single stage of voltage or power amplification normally is not sufficient for radio or radar. To obtain necessary gain, several stages must often be connected together. The output of one stage then becomes the input of the next throughout the series of stages, and the arrangement is called a cascade amplifier.

A cascade amplifier is designated according to the method used to couple one amplifier stage to the next. There are a number of methods, each having certain advantages and disadvantages, and the choice for a particular application depends on the needs of the aircraft. The basic methods are: (1)

resitance-capacitance, (2) impedance, (3) transformer, and (4) direct. The direct coupling was discussed in power supplies and requires no further discussion at this time.

224. Identify true statements for given coupling methods.

Resistance-Capacitance (RC). One of the most widely used methods of connecting amplifier stages is RC coupling, Amplifiers coupled in this manner are relatively inexpensive, lack heavy components, have good fidelity over a comparatively wide frequency range, are relatively free from undesirable induced currents from AC heater leads, and are especially suitable for use with pentodes and high-mu triodes.

An RC coupled amplifier can be designed to have good response for almost any desired frequency range. For instance, it can be designed to give fairly uniform amplification of all frequencies in the range from 100 to 20,000 Hertz. Slight modifications of the circuits can extend the frequency to cover the wide band required in video amplifiers. However, extension of the range can be obtained only at the cost of reducing amplification over the entire range. The RC method of coupling gives a good frequency response with minimum distortion, but it also gives low amplification.

A typical RC-coupled amplifier is shown in figure 3-27. The following names apply to the various circuit components.

R1 - Grid resistor.
R2 - Cathode bias resistor.
R3 - Plate load resistor.
R4 - Plate decoupling resistor.
R5 - Second-stage grid resistor.
C1 - Input coupling capacitor.
C2 - Cathode bypass capacitor.
C3 - Plate supply bypass capacitor.
C4 - Output coupling capacitor.

In order that the output voltage may be large, the load resistor should have as high a value as practicable. However, the higher this value becomes, the greater is the voltage drop across it

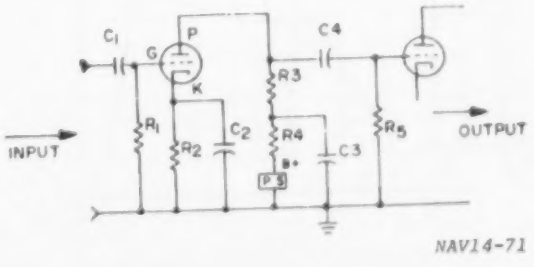


Figure 3-27. RC-coupled amplifier.

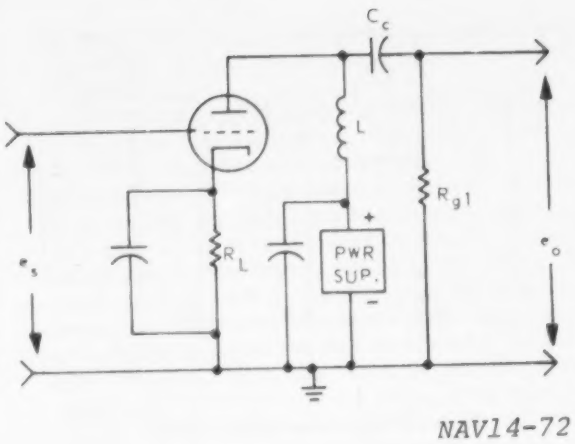


Figure 3-28. Impedance-coupled amplifier.

and the lower is the voltage remaining between the plate and cathode of the tube. To obtain the required effective plate voltage, the voltage drop across the load resistor is subtracted from the plate supply voltage. This places a practical limit on the size of the plate load resistor if the plate is to be supplied with its rated voltage. If a larger plate resistor is necessary, the only alternative is to increase the plate supply voltage. There is, or course, a practical limit to the amount that the plate voltage may be increased.

Impedance. Impedance or inductive coupling is obtained by replacing the load resistor R_L of a normal RC-coupled amplifier with a choke or inductor, L, as shown in figure 3-28. To obtain as much amplification as possible, particularly at lower frequencies, the inductor is made as large as practicable. To avoid undesirable magnetic coupling, a closed-shell-type inductor is used. Because of the low DC resistance of the inductor, a small DC voltage is developed across it. Thus, the tube will operate at a higher plate voltage.

The degree of amplification is not as uniform as it is with the RC-coupled amplifier because the load impedance, X_L, varies with the frequency. Since the output voltage appears across X_L, the voltage gain increases with the frequency up to the point where the shunting capacitance limits it. This is because $X_L = 2\pi FL$, where F represents frequency, L is the value of the inductor, and the Greek letter π represents a constant. The shunting capacitance includes not only the interelectrode and distributed wiring capacitances found in RC-coupled amplifiers, but also the distributed capacitance associated with the turns of the inductor. The distributed capacitance between the turns of the coil greatly increases the capacitance to ground and plays a part in limiting the use of this coupling at the higher frequencies.

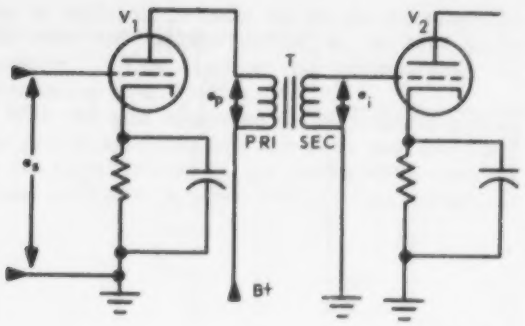


Figure 3–29. Transformer-coupled amplifier.

Transformer. A transformer coupled stage of amplification (shown in fig. 3-29) has certain advantages over other types of coupling. The voltage amplification of the stage may exceed the amplification of the tube if the transformer has a step-up turns ratio. Direct current isolation of the grid of the next tube is provided without the need for a blocking capacitor; and the DC voltage drop across the coupling resistor, which is necessary when RC coupling is used, is avoided. This type of coupling is also used to couple a high-impedance source to a low-impedance load, or vice versa, by choosing a suitable low secondary to primary turn ratio. Also, it may be used as a simple means of providing phase inversion for a push-pull amplifier without the use of special phase inverting circuits.

Transformer coupling has the disadvantages of greater cost, greater space requirement, the necessity for greater shielding, and the possibility of poorer frequency response at the higher and lower frequencies. The voltage gain as a function of frequency throughout the range in question is shown in figure 3-30. The curve shows that the transformer coupled amplifier has a high gain and uniform frequency response over the middle range of audio frequencies, but poor response for both low-audio and high-audio frequencies.

Exercises (224):

Identify the true statement for each coupling method.

—— 1. RC coupling gives low amplification.
—— 2. To obtain impedance coupling, replace the load resistor with a choke.
—— 3. With impedance coupling, higher tube voltages result.
—— 4. Transformer coupling can provide phase inversion of a signal.
—— 5. Isolation of DC is accomplished with transformer coupling.

3-10. Video Amplifier

A video amplifier is designed for uniformly amplifying a wide range, up to several megahertz. typical video amplifiers are RC-coupled circuits. They differ from audio amplifiers only in the values of the circuit components.

The RC-coupled amplifier shown in figure 3-31,a, presents several problems that must be solved before the RC-coupled amplifier can be used as a video amplifier.

225. Specify corrective action needed to improve the output of a malfunctioning video amplifier.

Frequency Characteristics. The high-frequency response of a video amplifier is limited by the output capacitance C_o, the distributed capacitance C_d, and the input capacitance of the following stage acting in parallel to shunt the load resistance, R_L. The low-frequency response, on the other hand, is limited by the time constant, $R_g C_c$, which must be long compared to the period of the lowest frequency to be amplified. Tubes with very low interelectrode capacitance must be used, and care taken in wiring the circuit to keep leads short and properly spaced in order to reduce distributed capacitance in the wiring. All of these problems are reduced by employing pentode tubes and by using small plate load resistors and frequency-compensating circuits.

The pentode circuit shown in figure 3-31,b, shows that the high frequency attentuating effect of high-input capacitance is practically eliminated in the pentode tube. The screen grid in the pentode tube forms an electrostatic shield between the plate and the grid. The capacitance between the control grid and the screen grid (C_{gs}) carries only a very small charging current since the screen grid voltage is maintained at a constant value. Both the C_{gs} capacity and also the C_{gk} (gird-to-cathode capacitance) are small. At high frequencies, current flow in these capacitances produces no noticeable

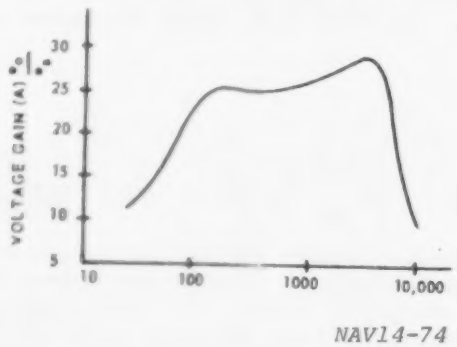


Figure 3–30. Transformer-coupled amplifier waveforms.

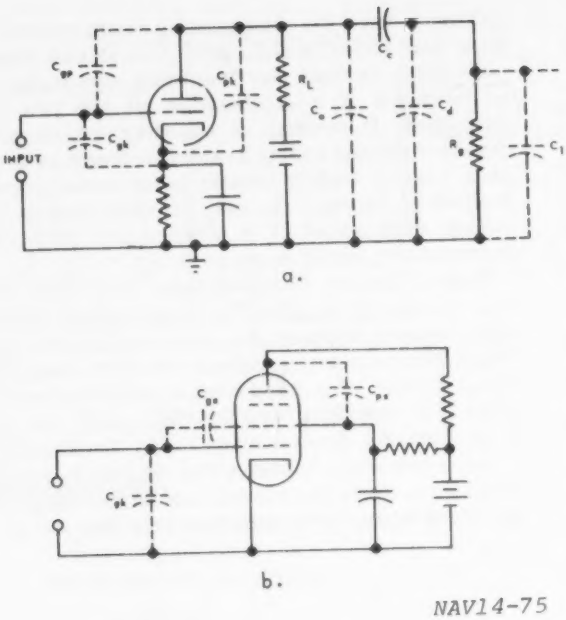


Figure 3-31. Effects of interelectrode capacitance.

attenuation. In addition to low-input capacitance, pentodes also offer the advantage of higher amplification than a triode.

Plate Load Resistors. The second circuit feature video amplifiers is the use of small load resistors. The size of the load resistor in RC-coupled amplifiers largely determines the frequency response and the gain of the amplifier. In this connection, figure 3-32 shows the effect of various sizes of load resistors on frequency response in a pentode amplifier stage. Notice that a large load resistor causes a high-output voltage at the middle frequencies and a steep drop in voltage at higher frequencies. In small resistors, the proportionate drop in voltage output (gain) at high frequencies is much smaller than a drop at middle frequencies.

The smaller proportionate drop at high frequencies, in the second case mentioned, results chiefly from the use of a small plate load resistor. The limit of amplification at the high-frequency end in an amplifier is controlled by capacitances that shunt the load resistance of the tube. These capacitances, which are called shunt capacitances, consist of the wiring, the socket, and the inherent capacitances of the tube. They act as a low impedance in parallel with the load resistor and effectively reduce the load impedance of the tube. For example, when the reactance of the shunt capacitance is equal to the reactance of the tube, the output voltage is reduced by half (two equal parallel impedances have a total impedance of half the individual impedances). In general, the higher the frequency, the lower the output impedance of the tube, and the lower the voltage output or gain.

This might lead you to conclude that it is not desirable to use plate load resistors of low-ohmic value, since at high frequencies the shunt capacitance reduces the output impedance enough without further decreasing it by small resistors. However, a video amplifier is primarily concerned with uniformly amplifying a wide band of frequencies, and only secondarily, with gain. To obtain a wide and uniform frequency response, there must be a sacrifice in gain. A small load resistor reduces the gain a high frequencies but at the same time, it improves frequency response. At the middle frequencies, the reactance of the shunting capacitance is not effective in reducing the output impedance of the tube, and the frequency response is fairly flat.

Low-Frequency Compensation. Video amplifiers must amplify frequencies at the low end of the band as well as at the high end. According to the frequency-amplification chart, figure 3-33, amplification of low frequencies shows improvements when the coupling

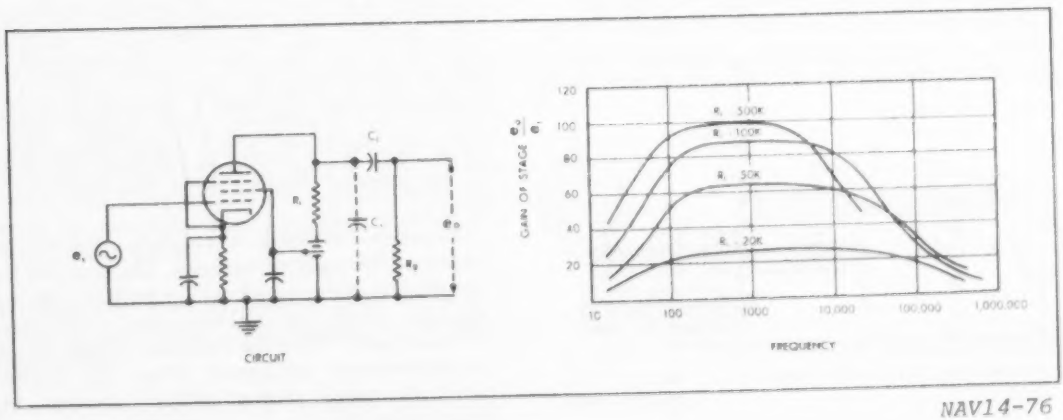


Figure 3-32. Effect of R_L size on frequency characteristics of amplifier.

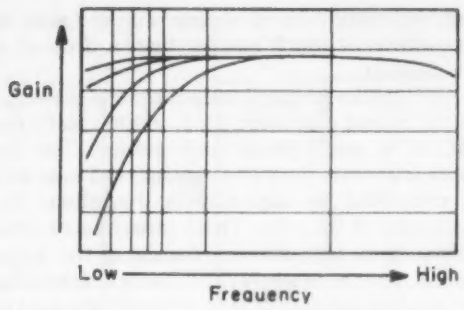


Figure 3–33. Coupling capacitor for low-frequency compensation.

capacitor C_c is large. A large capacitor has less reactance to low frequencies than a small capacitor, and low reactance means a smaller voltage drop. Since the coupling capacitor and the grid resistor form a voltage divider in the input circuit, more voltage appears across the grid resistor when the capacitor has a small reactance and greater amplification takes place. There is a limit to the increase in amplification possible by increasing the size of the coupling capacitor. A large C_c has capacitance to ground that affects the high-frequency response of the circuit.

A second more satisfactory means for improving low-frequency amplification is by using low-frequency compensating circuits, shown in figure 3-34. A low-frequency compensating circuit improves response because of the components C and R in series with the load resistor. C is comparatively large, and offers low resistance to middle and high frequencies and does not affect these frequencies. At low frequencies, its reactance is high and, in parallel with R, produces a reactance that increases the total load impedance. Earlier, you saw how the output voltage of an amplifier may be increased by increasing the load resistance. Since the compensating circuit produces a larger load impedance, the gain of the stage is higher.

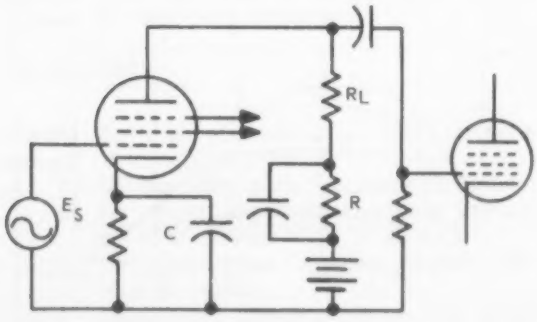


Figure 3–34. Low-frequency compensating circuits.

A third method for improving low-frequency amplification is a combination of the two just mentioned. It consists of adjusting the coupling capacitor size and adding a capacitive reactance in the plate load in such a manner as to obtain correct proportion between the two. In other words, the voltage drop across C_c is compensated for by the compensating circuit in the plate.

High-Frequency Compensation. The small plate load resistors of amplifiers do not completely improve high-frequency response; thus, carefully designed high-frequency compensating circuits are often used. This circuit consists of a low-reactance inductor placed in series with the load resistor (fig. 3-35). At low frequencies, the inductor offers a very low reactance, which is practically a short within the circuit. At high frequencies, its reactance is high and larger voltages are developed increasing the gain of the amplifier.

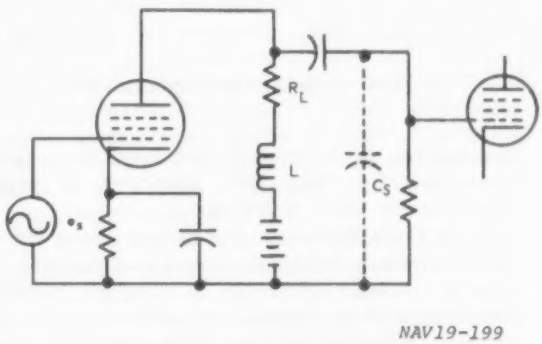


Figure 3–35. Shunt peaking coil.

Another similar compensating circuit, shown in figure 3-36, is called the series peaking coil circuit. The coil is connected in series with C_c. (Remember that the cause of reduced high-frequency voltage is the decrease in reactance of the stray capacitance in the circuit and the grid-to-cathode capacitance in the next tube C_s.) At high frequencies, the inductance L resonates with the stray capacitance and the grid-to-cathode capacitance (represented as C_s) causing an increased current through C_s, and a greater voltage across C_s that results in a higher gain.

Negative Feedback. Frequency response can be improved by negative feedback. This involves feeding a small part of the output voltage back into the input in opposite phase or polarity and proportionately reducing gain. When the feedback is large, the gain is proportionately decreased; when the feedback is small, the gain is proportionately increased. At high frequencies, the gain of an amplifier is decreased, less out-of-phase voltage is fed back to the input, and the gain is effectively increased.

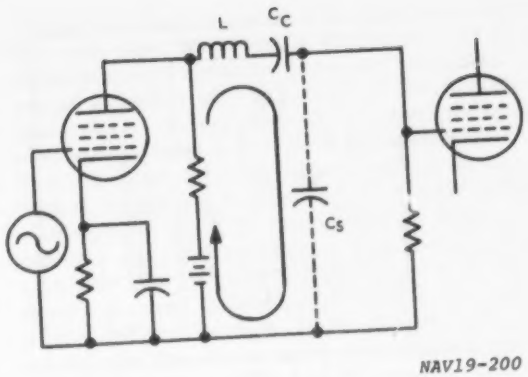


Figure 3-36. Series peaking coil.

Exercises (225):

1. Identify the component of column B that will correct the problem given in column A. More than one component may be used when required.

Column A Consideration Feature	*Column B Component*
_____(1) Excessive interelectrode capacitance.	a. Coil (series or shunt.)
_____(2) Steep drop in voltage at high frequencies.	b. Large R_L.
_____(3) Loss of input signal at low frequencies.	c. Small R_L.
_____(4) Gain and frequency response is poor at the high end of the band.	d. Small C_c.
	e. Large C_c.
	f. Use pentode tube.
	g. Parallel RC network in series with R_L.

3-11. Radio Frequency Amplifiers

Audio amplifiers are designed to amplify frequencies from about 15 Hertz to 16,000 Hertz. (See fig. 3-37.) Video amplifiers work in a range of frequencies from 30 Hertz to about 5,000,000 Hertz (5 MHz), and RF amplifiers amplify signals from about 30 kHz to 30 GHz. An outstanding feature of an RF amplifier is that it does not amplify this entire frequency range at once. It selects a *specific band* of frequencies and amplifies these while rejecting the unwanted ones. This, you recognize, is a job for the tuned circuits.

226. Using short answers, identify given RF and IF amplifier components, configurations, or amplifier characteristics.

RF amplifier circuits and IF amplifier circuits are essentially alike. They differ only in their use and frequency. IF amplifiers are designed for amplifying a very narrow band of frequency, usually higher than 100 kHz, while RF amplifiers amplify a wide band of frequencies on each side of the frequency for which they are designed.

Because of inefficiency of vacuum tubes at high frequencies, RF amplifiers are not normally used above 100 MHz frequencies. For low-power operation such as required in receivers, pentode RF amplifiers provide the highest gain with the least tendency to break into self oscillation. The amplifier shown in figure 3-38 is an IF amplifier, since it is designed to amplify only one frequency. Single-frequency amplification occurs because of the parallel resonant circuits at the input and output. These resonant circuits discriminate against all other frequencies by developing maximum voltage at their resonant frequencies. This ability of an amplifier to select one frequency and reject others is called *selectivity*. Selectivity in an amplifier is greatest when high Q tuned circuits are used. (A high-Q tuned circuit is produced here by using powdered iron cores in the transformers.)

The RF amplifier in figure 3-38,b, commonly used in transmitters. As contrasted with the circuit in figure 3,38,a, which uses a pentode tube, this circuit uses a triode. Another difference is that the tuned circuit is in the plate circuit only. The coupling circuit from the plate tank to the grid is a neutralization circuit to feed out-of-phase voltage from the output back into the grid circuit. Its function is to prevent the triode from oscillating.

Gain. The gain of a tuned Rf amplifier, using a variable mu tube, can be controlled by regulating the transconductance (g_m) of the tube. The two most widely used methods of gain control are illustrated in figures 3-39,a, and 3-39,b.

In figure 3-39,a, the gain is controlled by the magnitude of screen grid voltage. As the screen grid voltage is increased, the transconductance increases with a resultant increase of gain. When the screen grid voltage is decreased, the reverse action takes place, with a resultant decrease in gain.

The capacitor C_s between screen grid and ground in the circuit of figure 3-39,a, is called the screen bypass capacitor. Its purpose is to decrease degeneration due to the AC component of signal

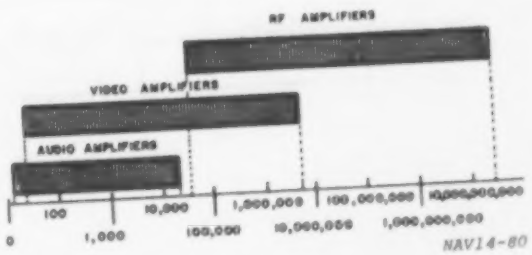


Figure 3-37. Frequency ranges of amplifiers.

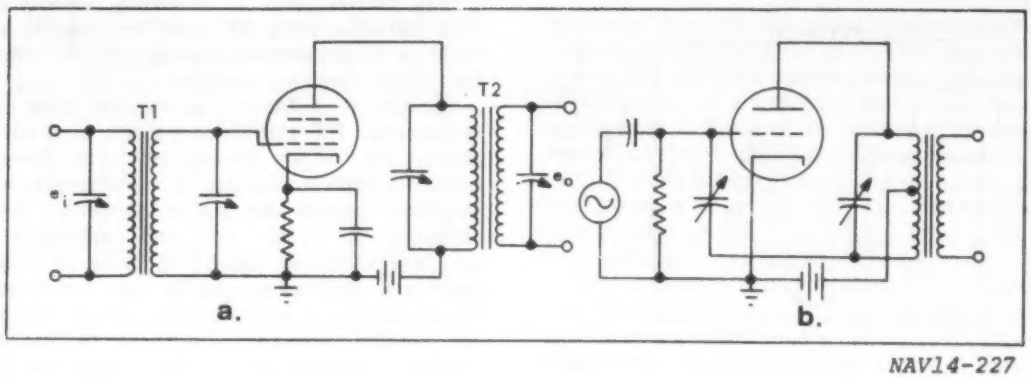


Figure 3–38. Typical IF amplifier.

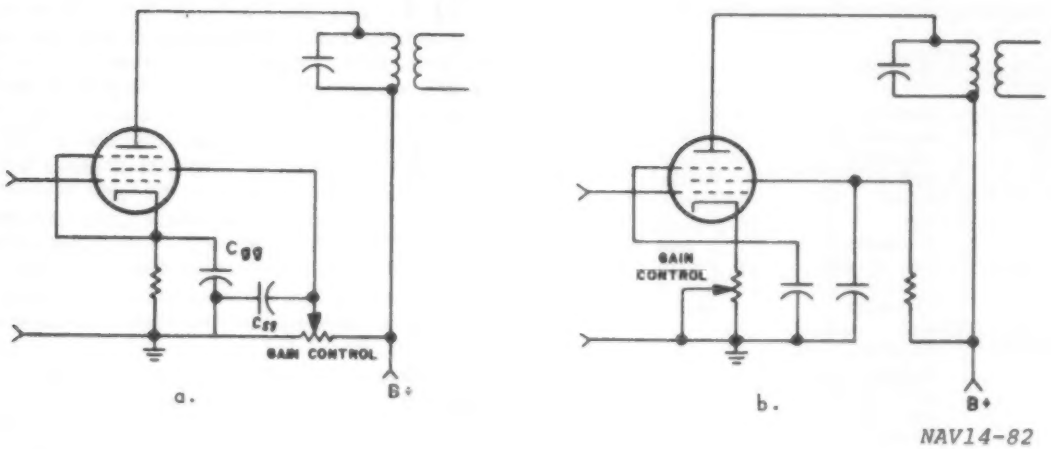


Figure 3–39. Gain control methods.

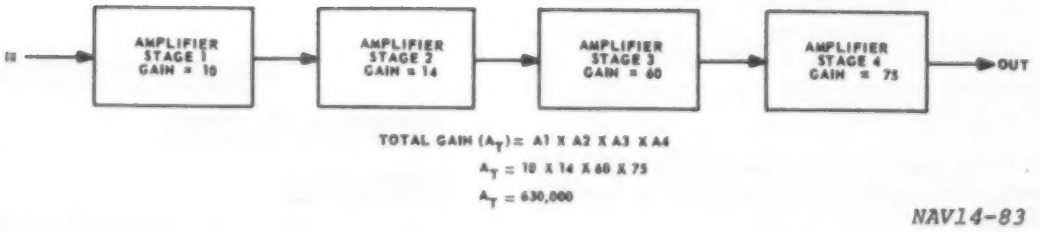

IN
AMPLIFIER STAGE 1 GAIN = 10
AMPLIFIER STAGE 2 GAIN = 14
AMPLIFIER STAGE 3 GAIN = 60
AMPLIFIER STAGE 4 GAIN = 75
OUT
TOTAL GAIN (A_T) = A1 X A2 X A3 X A4
A_T = 10 X 14 X 60 X 75
A_T = 630,000
NAV14-83

Figure 3–40. Cascade amplifier showing overall gain.

voltage causing the screen grid voltage to vary at the same rate. Its action is similar to that of the cathode bypass capacitor previously discussed. The bypass capacitor acts as a filter so that the screen grid voltage, in this case, will be relatively steady, even though there is an AC component in the tube. The effect of removing this capacitor would be evident in the plate circuit by a decrease in gain.

In figure 3-39,b, the cathode bias is regulated in order to control amplification. The change of gain with this type of control depends on a change of operating point. The amplifier is made to operate over a different position of its characteristic curve so that the mu of the tubes, and thus the gain, is changed. Many amplifier circuits using cathode bias to control gain use a variable mu tube. This type of tube is constructed so that its characteristic curve does not reach cutoff sharply, but rather at a gradual slope.

If the gains of individual amplifiers in cascade are known, the gains of all stages of amplification must be multiplied together. The block diagram in figure 3-40 illustrates this method of calculating the overall gain of amplifiers in cascade.

The power or current gain of a number of amplifiers in cascade can be found in the same manner if the amplification of each individual state is known.

Although current, voltage, and power gain (amplification), as well as their magnitudes relative to reference values, can be expressed as an ordinary ratio, it is more convenient to use logarithmic ratios. The unit that has been adopted is the decibel, which is indicated by the symbol dB.

The sign associated with the number of decibels indicates which power is greater; thus, a negative sign means P_{out} is less than P_{in}.

If decibels are used to express amplification, this simply means that the presence of the amplification increases the power output by the number of decibels attributed to the amplification. The practical value of the decibel arises from its logarithmic nature. This permits the enormous ranges of power involved in communications and radar work to be expressed in decibels rather than large numbers, but still allows small ratios to be expressed. Thus, 60 dB represents a power ratio of 1,000,000:1. The logarithmic character of a decibel also makes it possible to express the input and output powers of a number of amplifiers in cascade as the sum of the dB gains of the individual amplifiers. The block diagram shown in figure 3-41 illustrates this manner of computing the overall gain of an amplifier when the dB gains of the individual stages are known.

The decibel is also the natural unit for expressing sound intensities, since the effect sound waves have on the ear is roughly proportional to the logarithm of the intensity.

Operation. IF amplifiers are used in superheterodyne receivers. In these receivers, the incoming signal is converted into a new and lower frequency and amplified by specially designed, high gain IF amplifiers. Although communications receivers use intermediate frequencies as low as 75 kHz, the tendency is for them to use much higher frequencies because of poor image rejection at the lower frequencies.

Unlike communications receivers, which have a relatively narrow bandpass, radar receivers are designed with bandpasses as wide as 10 to 20 MHz. The usual practice is to use intermediate frequencies of 30 MHz and 60 MHz in radar receivers. Although high gain circuits are hard to design at these frequencies, the bandpass characteristics are good. The additional bandpass devices that must be built into the radar sets further reduce gain. In a radar receiver it is common to find six, eight, or more stages of IF amplification.

Previously, you saw that the video amplifier must be specially designed. Similarly, RF and IF amplifiers require special design. A pulse-modulated RF signal contains the RF frequency (or IF frequency) plus a sideband frequency for each of the frequencies in the pulse. All of these frequencies add up to a very wide band of frequencies. To accommodate them, the amplifier band must be fairly wide. The bandwidth of the amplifier may be increased by lowering the Q, stagger tuning, and overcoupling.

Classification. Amplifiers are classified as single tuned or double tuned, depending upon whether each interstage coupling circuit includes

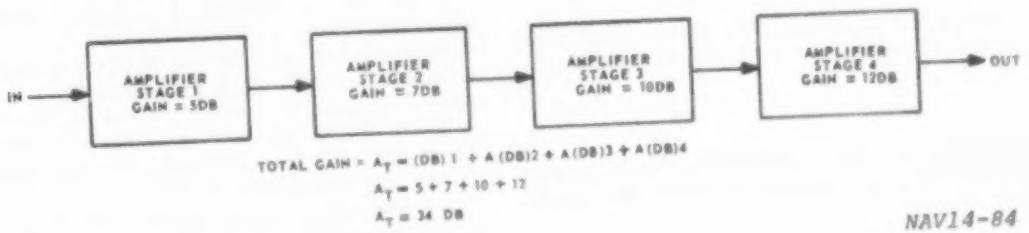

IN
AMPLIFIER STAGE 1 GAIN = 5DB
AMPLIFIER STAGE 2 GAIN = 7DB
AMPLIFIER STAGE 3 GAIN = 10DB
AMPLIFIER STAGE 4 GAIN = 12DB
OUT
TOTAL GAIN = $A_T = (DB)1 + A(DB)2 + A(DB)3 + A(DB)4$
$A_T = 5 + 7 + 10 + 12$
$A_T = 34$ DB
NAV14-84

Figure 3-41. Cascade amplifier showing dB gain.

one or two tuned circuits. Double-tuned coupling produces greater gain for a given bandwidth, but is *not* used often because of the greater simplicity in alignment and in manufacture of single tuned circuits. In both tuned circuits, transferring the desired signal is the prime consideration. The distance, or coupling, between the primary and the secondary, is physically designed by the manufacturer. External adjustments, whether capacitive or inductive, are physically situated for easy accessability. Keep in mind when adjusting, that adjustments are made in accordance with the specific system technical order. The illustrations in figure 3-42 show the circuit diagrams and equivalent circuits for both types of amplifiers for familiarization.

Similarities. RF amplifiers are similar to IF amplifiers except for tubes used at UHF frequencies. An RF amplifier is used when the signal-to-noise ratio of a radar receiver is not high enough. Several stages of IF amplifiers are used in radar receivers. Each succeeding stage narrows the bandwidth of the receiver. In receivers that use a bandwidth of 3 to 6 MHz, poor fidelity results from use of several stages in cascade, unless the bandwidth is increased. Increasing bandwidth may be accomplished by any of the following methods:

- Close coupling the transformers in double-tuned states.
- Loading the primary section of the transformer by making the value of R_L smaller. (R_L can be decreased only to a certain limit.)
- Tuning some IF stages slightly above the intermediate frequency and some slightly below (stagger tuning).
- Not using a bypass capacitor in the cathode or screen grid circuit.

Each of these reduces the gain and the input capacitance of each stage and results in an increase of the overall bandwidth. Remember, none of these methods can be used without reducing the gain of the IF amplifier.

Exercises (226):

1. Why is stagger tuning of IF stages used?

2. What is the advantage of a remote cutoff tube over a sharp cutoff tube as an RF amplifier?

3. Describe the gain control used on a remote cutoff tube and identify its use in the circuit.

4. What is the most noted circuit feature when the pentode tube is used as an RF amplifier?

3-12. Push-Pull Power Amplifiers

There are several advantages of a push-pull amplifier used as the output stage of an audio frequency amplifier. First of all, second harmonics, and all even numbered harmonics, are eliminated. Second, hum from the plate power supply is eliminated because ripple components in the two halves of the primary of the output transformer counteract each other in the output. Third, plate current flow through the two halves of the primary winding is equal and in opposite directions; therefore, there is no DC core saturation, and the low frequency response is improved. Fourth, regeneration is also eliminated because signal currents do not flow through the plate voltage supply when the circuit is operated as a Class A amplifier.

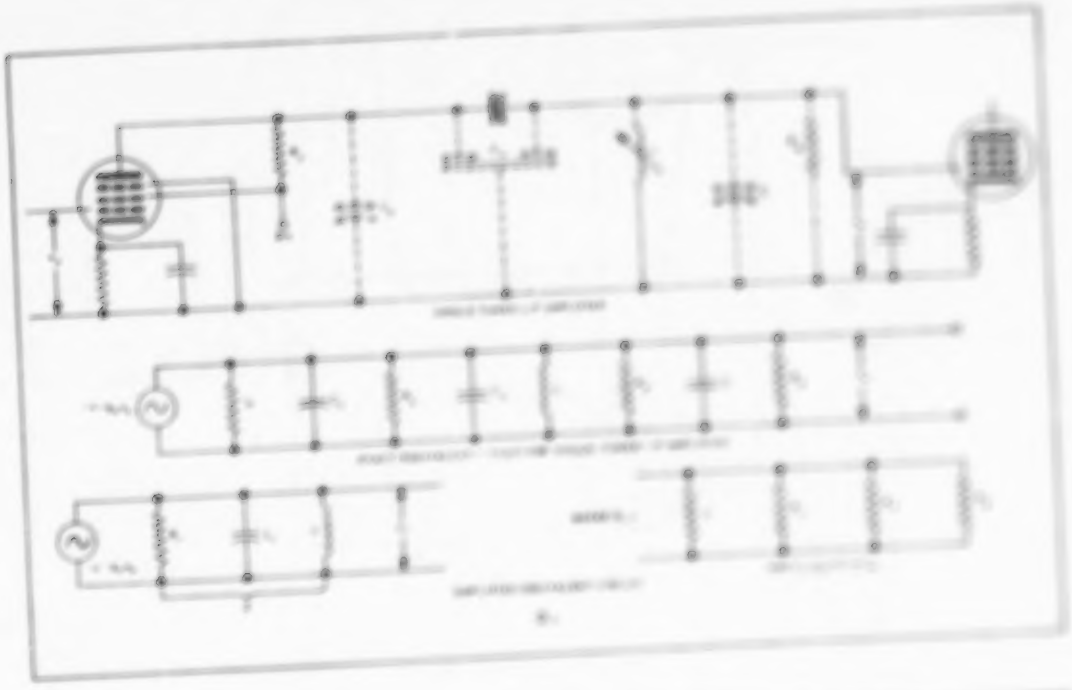
227. Specify operational characteristics for a given class of power amplifier operation.

Operation. Examine the circuit in figure 3-43. Notice that both transformers are center tapped—T1 in the secondary and T2 in its primary. Both tubes have the same bias voltage. Since the plate currents are equal and flow in opposite direction through the primary of T2, the effect is to produce a cancellation of the DC magnetization of the core. This increases the incremental inductance of T2 and makes possible the use of less iron in the core. Since the grid driving voltages are taken from the center tapped secondary of T1 with reference to point 2, e_{g1} and e_{g2} are of equal amplitude but 180° out of phase.

First consider the amplifier under no signal conditions. The grids have a negative bias, both cathodes are at ground potential, and the full output of the power supply is applied to the plate of each tube. Under this condition, points 4, 5, and 6 will be at the same potential (B+), with a heavy current flowing in each half of the primary of T2.

With an alternating voltage (e) at the primary of T1, we get a stepped up voltage across the secondary. Using point 2 as reference, we have equal voltage (e_{g1} and e_{g2}) 180° out of phase appearing at terminals 1 and 3. At a time when the voltage at point 1 is rising in a positive direction, the voltage at point 3 will increase in a negative direction. These grid voltages will result in current increasing in V1 and decreasing in V2.

We know that counter EMFs will be generated across the primary of T2. They will be of a polarity across the primary T2 such as to oppose the change producing them. Thus, point 4 will have a negative



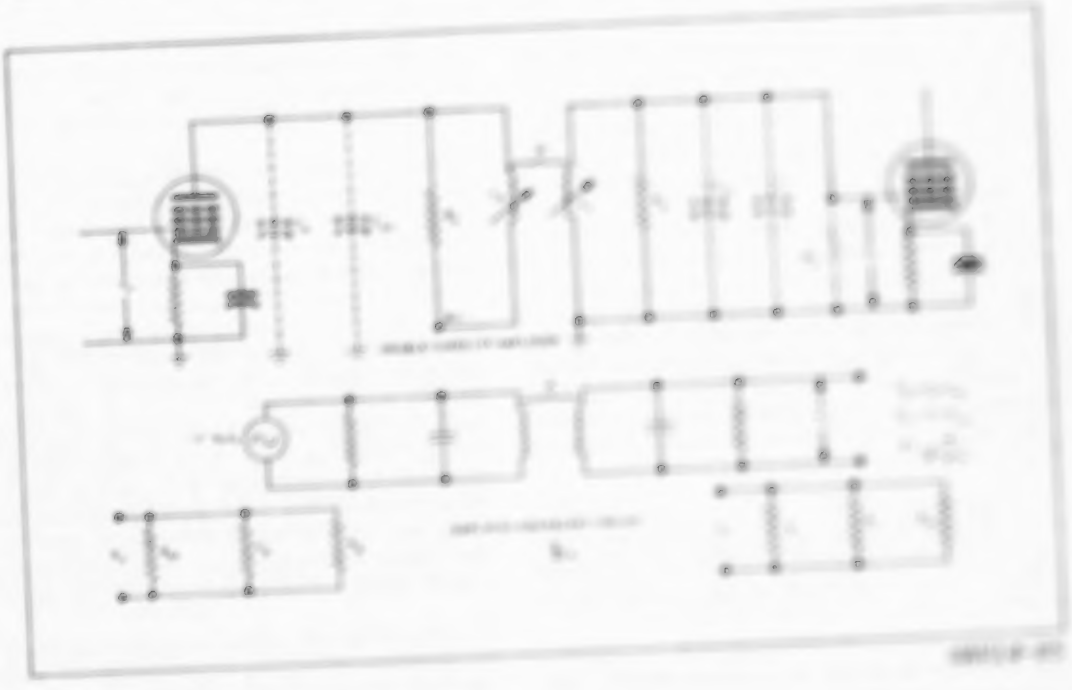
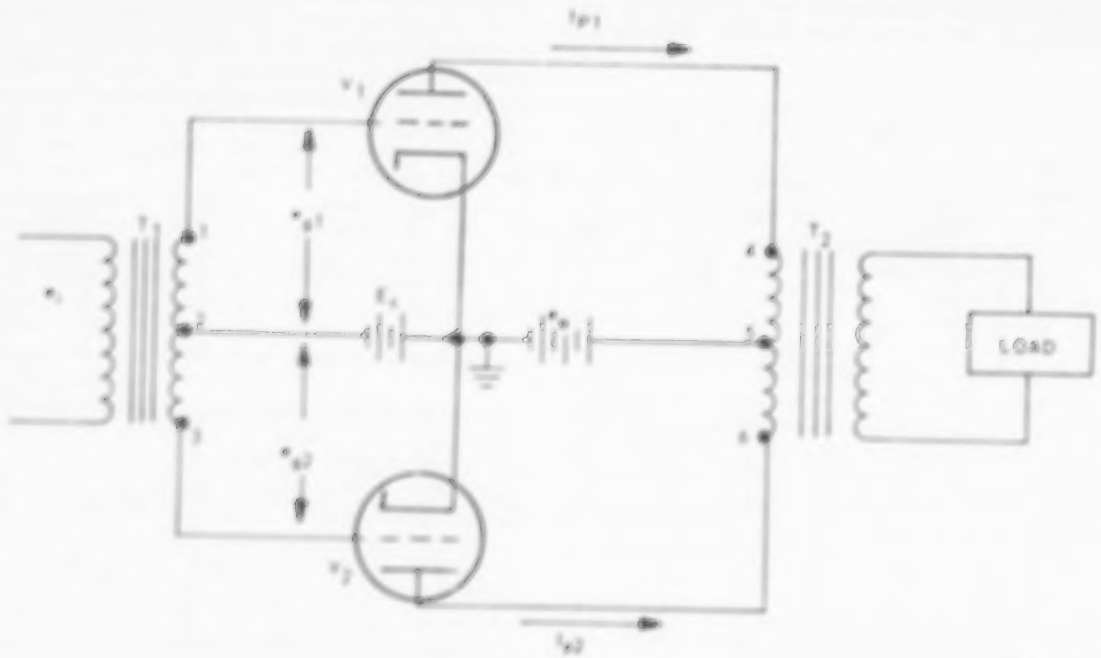


Figure 3-42. Tuned RC amplifier and equivalent circuits



NAVEDTRA

Figure 3-43. A push-pull amplifier.

going EMF since that is the polarity that will oppose an increase of current through V1. The decrease of current through V2 generates a positive-going EMF at point 6. This positive-going voltage will add to the potential of the power supply so that, with reference to ground, the plate voltage of V2 exceeds B+.

As the signal voltage passes through its cycle, it reverses polarity. Thus, e_{g1} becomes negative and e_{g2} positive, causing I_{b1} to decrease while I_{b2} increases. Point 4 will now have a positive-going counter EMF, while that at point 6 is negative-going. The alternating voltage across the primary of T2 will give an AC output to the load device. During both alternations, the total current from the power supply has remained constant. Thus, AC is kept out of the power supply.

The effects of the two tubes are added, with the result that the output is larger than it would have been with a single tube. The amplifier gets its name because, in effect, V1 is pushing the alternating current through the primary when V2 is pulling it, and vice versa.

Class A. Let us now proceed to a graphic analysis of the operation. In order to achieve Class A operation with 15-volt peak-to-peak signal, let us select a bias of 7.5 volts, which sets the operating point for each tube. Now we place the two dynamic curves together with one of them upside down, as shown in figure 3-44. The effect is that the tubes are 180° out of phase. The graphs are so positioned they coincide at the bias point (−7.5 volts), establishing the operating points 01 for V1 and 02 for V2.

Plate current at the operating point is 4.7 mA for each tube. Notice that e_g in the figure represents the signal voltages for each tube. The signal peak on the right of the bias line indicates a positive-going voltage applied to V1 and a negative-going voltage at V2. V1 reaches a maximum conduction of 1.5 mA, while V2 reaches a minimum conduction of 1.2 mA. This leaves a net effect of 8.3 mA as the AC peak current in the transformer primary. This current is represented at point A. As the signal peak moves to the left, V1 gets a negative-going voltage while that at V2 is positive-going. This results in a current peak of 8.3 mA in the reverse direction (point B). The dashed line drawn from A to B represents an idealized dynamic curve for the two tubes operating class A for the conditions stated. Applying our signal to it, we get the output L.

A curve for the actual dynamic conditions may be obtained by adding algebraically the values of the two dynamic curves. This results in a slender "reverse-S" curve passing from A to B through the bias point and differing slightly from the idealized curve.

Reduction of harmonics. You will recall that greater amplification for the positive signal peak

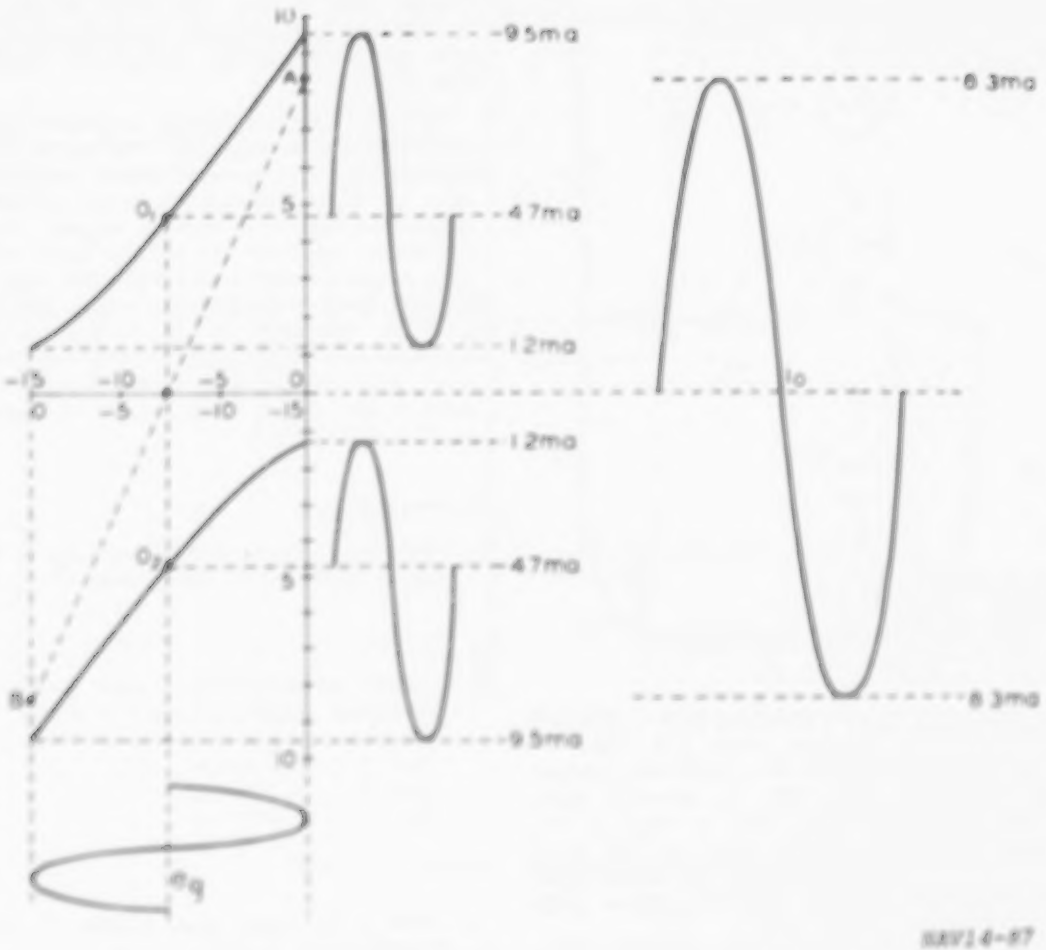


Figure 3-44. Dynamic curves of class A push-pull amplification.

class for the negative signal peak produces second-harmonic distortion. In our push-pull amplifier, each tube is introducing distortion. Second-harmonic distortion in class A amplifiers is found by dividing the peak-to-peak amplitude of the tube's AC output current into the change in the tube's average plate current caused by a signal. Multiplying by 100 gives the distortion in percent.

One outstanding advantage of the push-pull circuit is elimination of second-harmonic distortion and all even harmonics.

We have already seen that the actual dynamic curve is not a straight line. Therefore, output (i_b) is not a pure sine wave for the peaks are broadened, which indicates odd harmonic distortion. The third harmonic is the chief offender, resulting, like the second harmonic, from the nonlinearity in the tube characteristics as the bias is increased. This is particularly noticeable in pentodes and, to a lesser extent, in beam-power tubes.

Equivalent Circuits. Equivalent circuits for the push-pull amplifier in figure 3-43 are shown in figure 3-45. R_L is the resistance reflected into the primary of the output transformer (plate-to-plate) by the load at the secondary. At every instant, the polarities of the generators are in series aiding. This simply means the upper terminals of both generators have the same polarities and amplitudes at all times (see fig. 3-45,a). The bottom terminals will likewise go through their cycles in the same way. Thus, the circuit may be simplified as shown in figure 3-45,b.

Because push-pull circuits cancel most of the distortion found in single-ended class A amplifiers, it is no longer necessary to make each tube operate with a load resistance twice the value of the plate resistance. This means we may select the value of R_L that will give maximum power transfer, which is at the point where $R_L = r_p$. For two tubes, then, the value is doubled and R_L for the two tubes equals

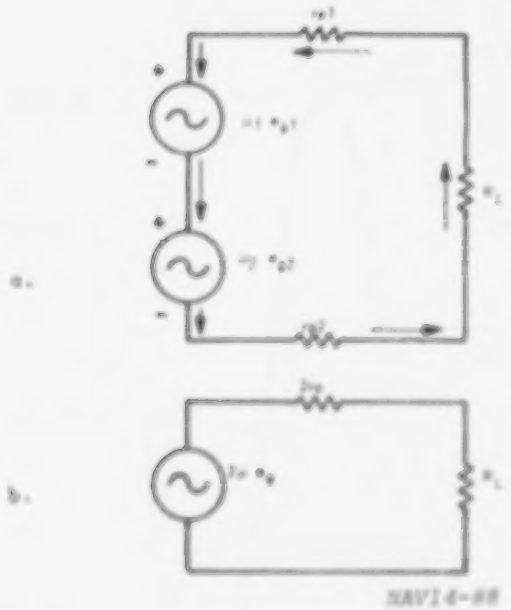


Figure 3-45. Equivalent push-pull circuits.

2 r_p. Thus, two triodes operating class A push-pull are capable of handling about 2.25 times the undistorted power output of a single tube operated class A. At the same time, the push-pull circuit requires a signal voltage twice as large as that demanded by a single tube, since only half of the voltage is applied to either grid. The largest signal the circuit can handle is when the positive peaks equal the bias.

Class B. Push-pull amplifiers are also operated class B. For a graphic presentation, use the curves in figure 3-46.

At first glance, class B operation may seem a disadvantage, since we are now using a 30-volt peak-to-peak signal and getting the same output current (i_b). Notice, however, that both tubes are biased to near cutoff. The no-signal plate current has been reduced from 4.7 mA to 1.2 mA. Therefore, plate dissipation is also reduced. V1 is now, in effect, amplifying only the positive-signal peak, while V2 amplifies the negative signal peak, and drives the tube harder while it is conducting. Using a smaller load impedance results in a steeper dynamic curve. Thus, the signal voltage shown will actually result in a larger peak plate current than is indicated. Because only one tube is conducting at a time, the output follows the sine wave input more closely.

Class B operation has the advantages of handling larger signal voltages, giving greater output power, and having practically no distortion. It requires, however, a well-regulated power supply since signals produce a wide range of changes in the average plate current. This latter feature makes cathode biasing undesirable; therefore, several tubes have been developed that operate near cutoff with zero bias.

Class C. Class C push-pull amplifiers find their greatest usage in the range of RF. With the tube biased to approximately twice the cutoff voltage, conduction will occur only on the positive peaks, giving a very distorted output. Such amplifiers, therefore, use parallel resonant circuits for a plate load. The peaks, or pulses, are made large enough to keep the swinging action going in the resonant circuit. Since parallel resonant circuits offer maximum impedance at the resonant frequency, harmonics receive little if any amplification. Thus, the action of the resonant circuit restores the shape of a sine wave to the output. These circuits are capable of handling great power.

Exercises (227):

1. What kind of plate load is found in a push-pull power amplifier operating class C?

2. Identify the percentage of input signal that a push-pull amplifier tube conducts when operating:
   Class A _____ .
   Class B _____ .
   Class C _____ .

3. What is the largest signal a class A push-pull amplifier can handle?

4. What class of operation for a push-pull amplifier eliminates regeneration?

5. In what frequency range does the class C amplifier find its greatest usage?

3-12. Cathode Follower

A cathode follower is a single-stage degenerative amplifier. The output is taken from the cathode resistor, as shown in figure 3-47. This circuit is for matching a high-impedance circuit to a low-impedance circuit without discriminating against any AC frequency. Its voltage output is always less than the input voltage, but is capable of power amplification. Two advantages of cathode followers are low-input capacitance and distortionless output.

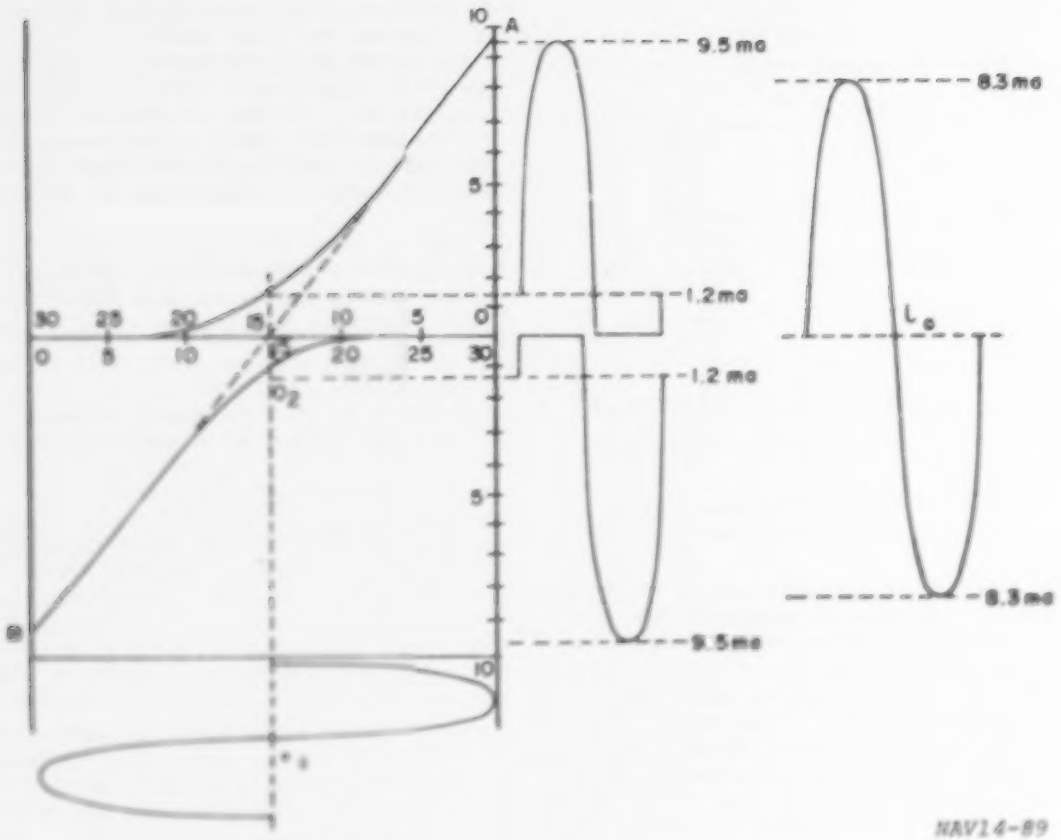


Figure 3-46. Dynamic curves of class B push-pull amplifier.

2-28. Identify operation characteristics of cathode-follower circuits.

Input. As previously mentioned, series losses result from the high-input capacitance a triode takes. This is because the resistive load causes a leading current in the grid circuit, and the plate-to-grid capacitance adds to the normal grid-to-cathode capacitance to produce a large capacitance at the input of the triode. Unlike the triode, the gate load to the cathode follower is a large capacitance (usually the filter capacitor in the power supply). The current in the grid circuit does not lead because the capacitive load in the cathode follower causes the charging current to shift in phase and puts it exactly in phase with the original grid voltage. Since adding in-phase current is the same as lowering the resistance in the grid circuit, the impedance reflected in the grid circuit is purely resistive, and its effect on all frequencies in the range, that is, there is no frequency attenuation.

Output. Another advantage is that cathode followers introduce little amplitude distortion into the output. It is a degenerative circuit in which negative feedback is always produced by an unbypassed cathode resistor, and its output is taken from across the cathode resistor.

Design Considerations. Three of the most important considerations of cathode followers are gain, input and output impedances, and size of the cathode resistor.

Gain. The gain of a cathode follower is less than one, but it applies only to AC voltages and not to DC values. Actually, the cathode-to-ground DC voltage is greater than the input voltage as long as the grid-to-cathode voltage is negative.

Impedance. The input impedance in a cathode follower is high. Since cathode followers are operated with the grid negative with respect to the cathode, a high-amplitude voltage can be applied between the grid and ground without causing grid current flow. This is due to the degenerative action of the cathode resistor and the high input impedance during the positive input signal. Because of its high-input impedance, the cathode follower

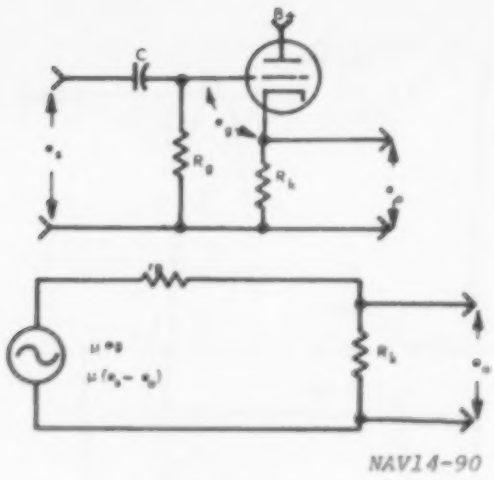


Figure 3-47. Cathode follower with equivalent circuit.

has negligible loading effect on the circuit that drives it. The output impedance is low.

The equivalent circuit is redrawn in figure 3-48 to show the new circuit constants.

The output impedance of the cathode follower is the parallel combination of the cathode resistance and the effective AC plate resistance. In general, the output impedance is considered resistive.

Cathode resistor. The size of the cathode resistor is an important consideration in that it largely determines the output impedance, a factor of special concern in impedance matching.

Advantages. As previously stated, one of the principal advantages of a cathode follower is that it can be used to match a high impedance to a low impedance. Thus, it can take the voltage developed across a high impedance and supply a low-impedance load with only a slightly less voltage, but with a corresponding large increase in current. One or more of the circuit elements of a cathode follower may be varied to achieve a more precise impedance match if the match is critical.

When high mutual conductance tubes are used, the low value of output impedance extends the amplification into the upper range of frequencies because the shunting effects of interelectrode and distributed capacitances are proportionately smaller. The low-frequency response is improved by allowing the DC component of cathode current to flow in the load, thus avoiding the use of a series blocking capacitor.

The degenerative effect caused by the unbypassed cathode resistor increases the input impedance. Less shunting effect is offered to the previous stage, and a better overall frequency response is produced.

The input and output voltages have the same instantaneous polarity. When pulses are used, it may be necessary to feed a positive-going or negative-going pulse to a load without polarity inversion and to afford an impedance match.

Circuit stability is also improved by degenerative feedback. Specifically, amplitude distortion occurring within the tube, the effect of plate-supply voltage variations, aging tubes, production of harmonics and other undesirable effects that occur within the stage are counteracted by this type of circuit.

However, these advantages are achieved at the expense of an overall reduction in voltage gain. The voltage gain is slightly less than unity, but the circuit is capable of producing a gain in power.

Exercises (228):

1. What is the phase relationship of the input to the output signal of a cathode follower?

2. What are the three most important considerations in the design of cathode followers?

3. Identify the following statements as true or false as related to cathode-follower operation.
   - ___ a. The voltage gain of a cathode follower is less than unity but it is capable of producing a gain in power.
   - ___ b. The cathode follower can serve two purposes—prevent polarity inversion and match impedance.
   - ___ c. Distortion in a cathode-follower circuit is nearly nonexistent due to regenerative feedback developed across the cathode resistor.

3-14. Phase Inverters

A phase inverter is a circuit, or device, that changes the phase of a signal by 180°. One type is the transformer with which the instantaneous polarity of the load may be reversed with respect to the source by reversing either the connections of the secondary leads to the load or the primary leads of

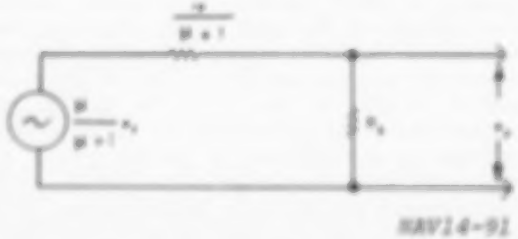


Figure 3-48. Equivalent circuit.

the source. A conventional electron-tube amplifier (untuned and RC-coupled) also produces an output of opposite polarity to the input. Another way to obtain phase inversion is through amplifier stages. Either single-tube or dual-tube amplifiers may be used to convert one input waveform into two output waveforms of opposite polarity. Such amplifiers are called phase splitters or paraphase amplifiers.

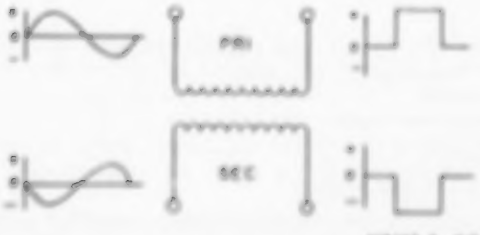
229. Specify operational characteristics of phase inverter methods.

Transformer. In operation, all transformers produce across the secondary an induced EMF that is opposed to the change in flux producing it. The instantaneous polarity of the actual output voltage across a low depends on how the leads from the secondary are connected.

Figure 3-49 indicates phase inversion of square waves and sine waves. With square waves, the polarity has simply been inverted. This is also true for sine waves, but in this case it is more convenient to refer to the inversion as a 180° phase shift; in effect, it is the same result as if the waveform had been moved along the time axis 180°. If no change in voltage is desired, a 1-to-1 turns ratio is used.

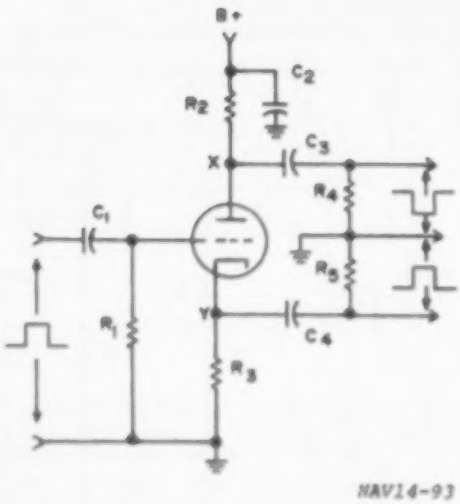
A transformer with a center-tapped secondary is used in class B push-pull amplifiers. This type of transformer phase inverter has limited application because of distortions and losses inherent in transformers. For example, the loss in voltage through leakage reactance is greater for higher frequencies than for lower frequencies. The shunting capacitance effect and hysteresis losses also increase with frequency. In many circuits where harmonics must be transmitted unattenuated and undistorted, the transformer phase inverter is replaced with a circuit that performs phase inversion without the use of transformers such as the paraphase amplifier.

Single-Tube Paraphase Amplifier. A form of single-tube paraphase amplifier is shown in figure 3-50. The values of R2 and R3 are the same. Therefore, the voltage drop across both of them is the same, since the same plate current flows through both. The instantaneous polarities, however, are exactly opposite



NAV14-92

Figure 3-49. Transformer phase inversion.



NAV14-93

Figure 3-50. Single-tube paraphase amplifier.

because at the instant a positive-going signal is applied to the grid, point X becomes less positive with respect to ground and point Y becomes more positive. These signals, with the polarities indicated in the figure, are impressed across load resistors R4 and R5 through C3 and C4. C2 is the plate supply bypass capacitor. In this circuit R3 provides a cathode self-bias. Since there is an AC voltage developed across R3, degeneration is produced and felt upon the cathode of the tube. The effect of this degeneration causes the voltage felt at the output terminals to be less than the input signal voltage, thus giving the single-tube paraphase amplifier a voltage gain of less than one (unity). Although this degeneration causes the circuit to have a gain of less than unity, it enables the stage to have good fidelity.

Two-Tube Paraphase Amplifier. A two-tube paraphase amplifier is shown in figure 3-51. Tube V1 operates as a conventional amplifier having normal gain, and V2 operates as a phase inverter, the input of which is reduced to the same value as the input of V1. V2 amplifies the signal as much as V1, and the output is essentially symmetrical about the zero-voltage reference line.

A positive-going signal on the grid of V1 causes an increase in plate potential at point X. This reduction in positive potential is transmitted as a negative-going signal through coupling capacitor C4 to R6 and R7. The grid input of V2 is connected between R6 and R7 to feed the proper magnitude of negative-going signal to V2. For example, if V1 and its associated circuits have a voltage gain of 50, the resistance of R7 should be 1/50 of the total value of R6 plus R7. At the instant a positive-going signal is applied to the grid of V2, a negative-going signal is applied to the grid of V2. The positive potential at point Y is increased, and a positive-going signal is applied to R8, through C5. At the same time, the negative-going signal appears across resistors R6 and R7.

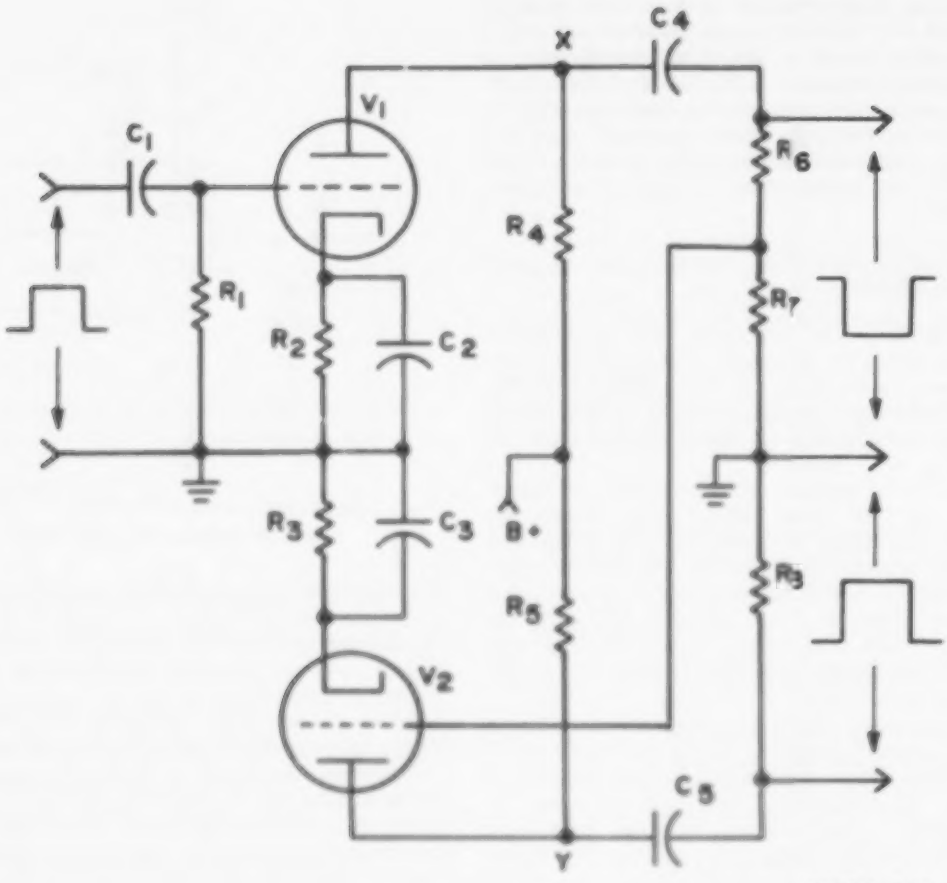


Figure 3-51. Two-tube paraphase amplifier.

If the operating conditions of the two tubes are carefully chosen and the circuits are properly adjusted, the two amplified output signals should be essentially undistorted and of opposite instantaneous polarity. In actual practice, this method presents some difficulty because the adjustments are critical. However, it is widely used as a means of driving class A push-pull power amplifiers.

Exercises (229):

1. At what frequencies is a transformer less efficient when it is used as a phase inverter?

2. With a negative-going input to a two-tube paraphase amplifier, as illustrated in figure 3-51, what will be the polarity of the signal between C5 and R8?

3. What is the major sult of a single-tube paraphase amplifier?

4. Where are the outputs taken in a single-tube paraphase amplifier?

5. Where are the outputs taken in a two-tube paraphase amplifier?

3-15. Oscillators

An oscillator is an amplier stage that generates a given frequency determind by the value of its components, and it maintain that frequency within certain limits. Positive feedbck is used to reinforce

the action in the stage and to replenish the power lost during the generation of each cycle.

Feedback may be accomplished in various ways to sustain oscillations. The following devices are used as feedback networks for this purpose.

- Transformer.
- RC and LC networks.
- Interelectrode capacitances.
- Additional vacuum tubes.

Each of these have characteristics that make their use advantageous under certain conditions. By using components of proper values, oscillators may be designed to generate frequencies from the low-audio frequencies to the very high radio frequencies.

Most oscillators may be classified as either tuned inductance-capacitance (LC) type or relaxation resistance-capacitance (RC) types. For highly stable frequency characteristics, some oscillators utilize a crystal, metal bar, rod, tuning fork, or other essentially constant source of vibrations as a frequency reference. Oscillators of this type are sometimes referred to as electromechanical oscillators. Our discussion of oscillators will begin with the LC oscillators.

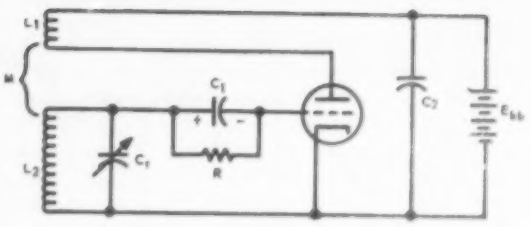
230. Specify the purpose and characteristics of an LC oscillator.

LC Oscillators. Electron tube LC oscillators use a tuned LC circuit connected as a series or parallel resonant (tank) circuit to determine the frequency of operation. An electron tube amplifier supplies pulses of energy of the proper phase and magnitude to maintain the oscillations. Operation is normally in the radio-frequency range.

Types. One of the simplest types of LC oscillator circuits is the tickler coil (Armstrong) circuit shown in figure 3-52. Feedback voltage of the proper phase from the plate to the grid circuit is accomplished by mutual inductive coupling between the oscillator tank coil, L2, and the tickler feedback coil, L1. The amount of feedback voltage is determined by the amount of flux (M) from L1 that links L2. The feedback voltage is varied by moving L1 with respect to L2 or by changing the setting of a variable resistor that is sometimes across L1.

The frequency-determining part of the oscillator is the tank circuit L2 C_t (E_t). The coil and tuning capacitor interchange energy at the resonant frequency rate and the excitation voltage developed across the resonant tank L2 and C1 is applied to the grid in series with the grid-leak bias across RC1.

Grid current flowing through R establishes negative bias on the grid. Capacitor C1 charges up to the peak voltage across R and holds this voltage between RF pulses because of the relatively long



NAV19-127

Figure 3-52. Tickler coil oscillator.

time constant of RC1 as compared with the time for each RF cycle. A steady bias voltage is therefore developed when the oscillator is functioning properly. One test for proper operation is a measurement of the DC voltage across the grid resistor. To avoid blocking the oscillations, a high-resistance-type meter, such as the electron-tube voltmeter, should be used for this measurement.

Hartley. There are two forms of Hartley oscillators—the series-fed and the shunt-fed. In the series-fed Hartley, direct current flows through part of the tank circuit. In figure 3-53,A, note that the tube is a portion of the tank circuit and that the tube and the power supply form a series circuit. In the shunt-fed Hartley, figure 3-53,B, direct current does not flow through any part of the tank circuit. The plate supply voltage is in parallel with the tube and tank circuit. The RF is kept out of the tank plate supply by an RF choke, and DC is kept out of the tank circuit by a blocking capacitor. The shunt-fed is safer for testing, because DC is eliminated from the core.

In Hartley oscillators, the frequency of oscillations is determined by the LC constant of the resonant tank circuit. Bias for the tube is provided by the grid-leak combination R1 and C1. Grid-leak bias, or a combination of grid-leak bias and fixed bias, is used since oscillators operate class C to secure high output and efficiency. When grid-leak bias is used, the bias is initially zero and plate current flows immediately. After oscillations build up, the grid-leak bias is equal to the RF voltage across the grid tank circuit and maintains a stable oscillation.

Voltage for sustaining oscillations in the Hartley oscillator is fed from the tank circuit to the grid circuit by mutual inductance between the plate and grid coils. Adjusting the position of the taps connecting the grid, cathode, and plate leads determines the magnitude of the feedback.

Colpitts. The Colpitts oscillator is essentially the same circuit as the Hartley oscillator except that a pair of capacitors in series is connected across the tank coil. C1 and C2 in the circuit in figure 3-53,C, forms a voltage-divider circuit that divides the voltage across the resonant circuit into two parts. The voltages at the ends

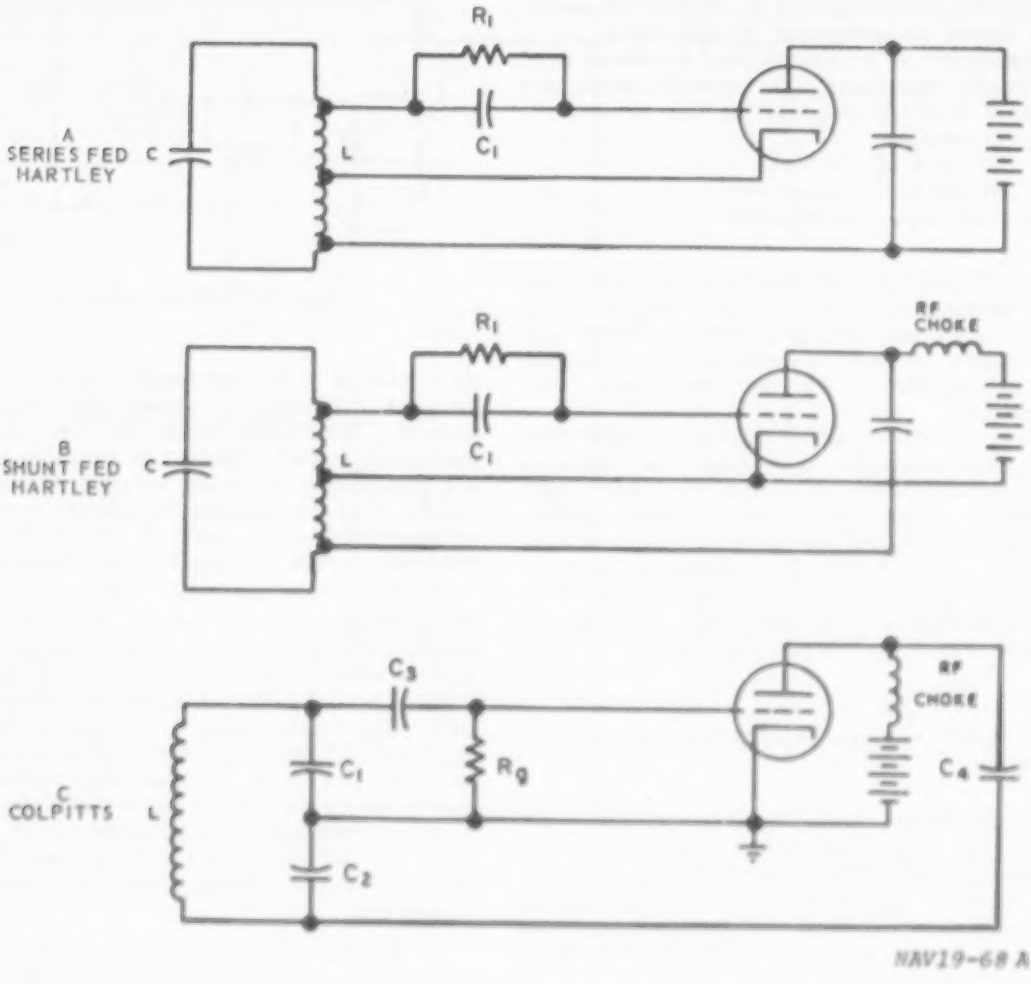


Figure 3-53. LC oscillators.

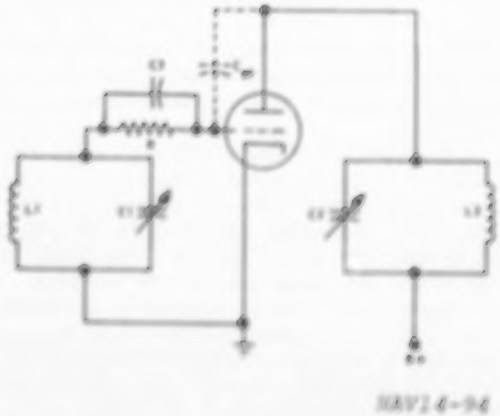


Figure 3-54. TPTG oscillator.

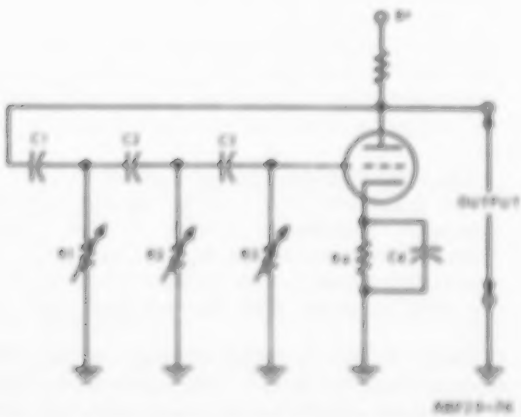


Figure 3-55. Phase-shift oscillator.

of the resonant circuit are opposite in polarity with respect to the cathode and in the right phase to sustain oscillation. The total tank capacitance consists of C1 and C2. C3 and R_g constitute the grid-leak bias combination.

Tuned-plate, tuned-grid oscillator. The tuned-plate, tuned-grid oscillator (TPTG) has tuned circuits in both the grid and plate circuits. This oscillator is used at ultra-high frequencies as well as low frequencies. (See fig. 3-54.)

The inductance in the plate tank circuit is not inductively coupled to the inductance in the grid circuit. The feedback necessary for sustaining oscillations occurs through the interelectrode capacitance between the plate and grid of the tube. This circuit automatically oscillates at a frequency lower than the natural frequency of both the plate tank and the grid tank. The tank that is tuned to the lower frequency, whether it is the plate or the grid tank, controls the oscillator frequency. The other circuits mainly affect the magnitude of the feedback voltage.

Exercises (230):

1. What is the primary frequency-determining device in LC oscillator circuits?

2. Identify the oscillator circuit most likely used in ultra-high frequencies.

3. Which part of a tickler coil oscillator is the frequency-determining device?

4. What characteristics in the shunt-fed Hartley oscillator makes it safer for testing?

5. Identify the components required for feedback in a TPTG oscillator.

231. Specify the characteristics and use of RC oscillators.

RC Coupled Oscillators. Many oscillators use resistance-capacitance networks to provide regenerative coupling between their output and input circuits and to determine the oscillation frequency. Such oscillators are called RC oscillators. Examples of RC oscillators are the phase-shift oscillator, the Wien bridge oscillator, and the free-running multivibrator discussed in the next chapter.

Phase-shift. The phase-shift oscillator circuit (fig. 3-55) consists of a single amplifier tube and a phase-shifting feedback circuit. An oscillator requires that the signal fed back from the plate to the grid be shifted 180° in order to sustain oscillations. In phase-shift oscillators, this function is performed by resistance-capacitance sections.

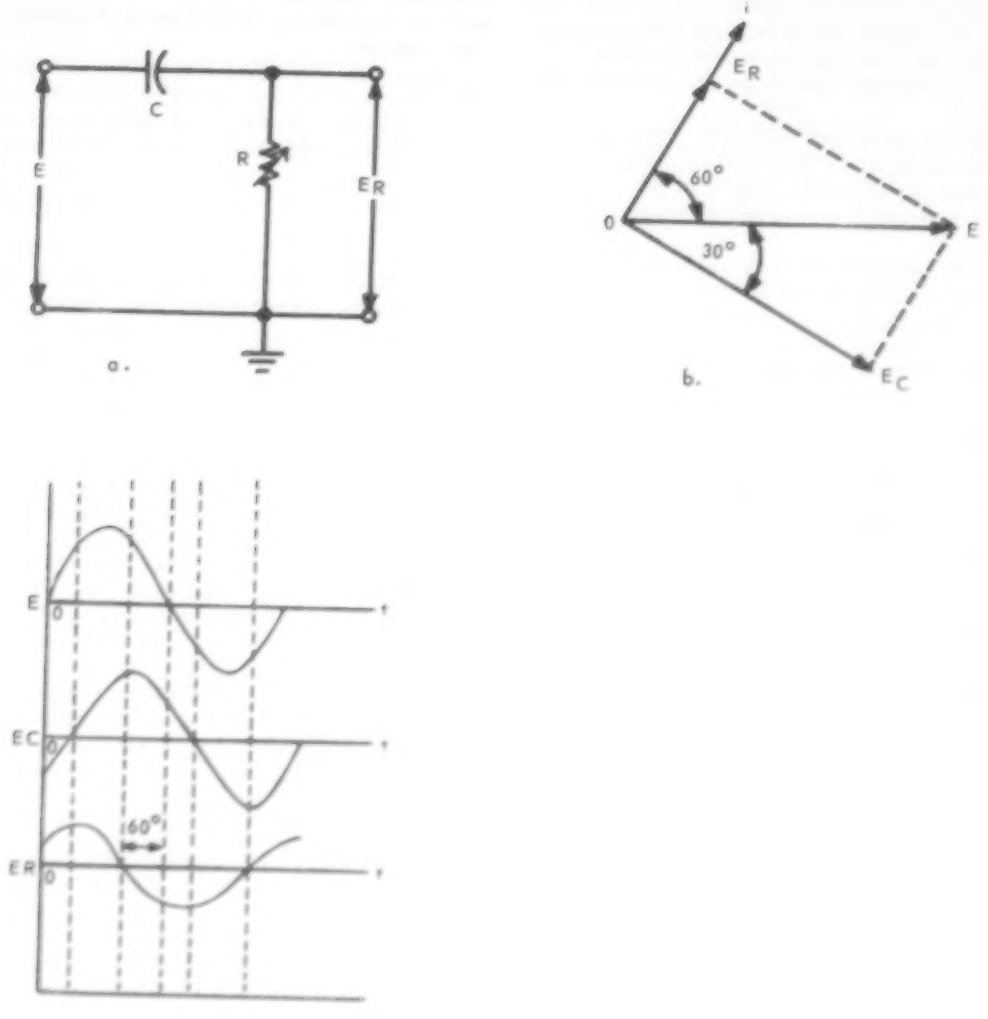
One of these sections is shown in figure 3-56. When an alternating voltage is applied to this circuit, current flows in the circuit. Since the circuit impedance is capacitive, the current leads the impressed voltage E. The voltage drop, E_R, across resistor R is in phase with the current that flows through it. Therefore, the voltage, E_R, also leads the impressed voltage by the same phase angle (60° is shown in b and c of fig. 3-56).

When the resistance of R is varied (Fig. 3-55), the phase angle of the current flowing in the circuit is also varied. If R were reduced to zero, the current would theoretically lead the applied voltage by 90°; however, adjusting that would be impractical. First, because reducing R to zero would leave no impedance for developing a useful voltage; and second, because R equals zero, the current would lead the voltage by slightly less than 90° because of the inherent circuit resistance and become a degenerative signal. This means that there must be a minimum of three RC sections in the phase-shifting network to produce a 180° phase shift.

When the output of the first section of figure 3-55, is applied to a second phase shifter, another shift of the output voltage occurs. R2 can be adjusted to make the output voltage of the second section the desired phase angle ahead of the voltage applied to the first phase shifter. When the output of the second phase shifter is fed to the third, another phase shift occurs. R3 is adjusted to make the voltage output 180° ahead of the voltage at the input to the first phase shifter.

The oscillations are started in this oscillator by any slight circuit change, such as variations in the plate supply or random noises. When such disturbances occur, the slight change is amplified and inverted 180° at the plate. One frequency is inverted another 180° by the RC network, from which it is returned in phase to the grid of the tube for reamplification. This process continues until plate-current saturation is reached where the tube cannot amplify further.

The frequency for which the network furnishes a 180° phase shift may be adjusted by varying one or more of the capacitors or resistors, the frequency being inversely proportional to the product RC. These oscillators are widely used below 20 kHz, where the elimination of inductances saves in weight, size, and cost.



NAV19-75

Figure 3-56. Phase-shift oscillator waveforms.

Wien bridge. The Wien bridge oscillator (fig. 3-57) is a two-tube oscillator, tuned by a resistance-capacitance bridge. V1 serves as an oscillator and amplifier, and V2, the other tube, serves as an inverter. This circuit would oscillate even without the resistance-capacitance bridge because of the 180° pase shift produced by tubes V1 and V2. However, this system would oscillate over a very wide rage of frequencies. The bridge circuit is used to insure the elimination of all feedback voltages except he voltage having the desired frequency.

Refer to the circuit in figure 3-58, which is another way of drawing the same circuit. A degenerative feedback voltage is provided by R3 and lamp L_{P1}. The amplitude of this feedback voltage remains nearly constant for all frequencies since the resistances are practically constant for all frequencies and since there is no phase shift across the voltage divider.

The inverter shifts the output of V1 by 180°, and the voltage appearing across R2 of the bridge is in proper phase to sustain oscillations. This action occurs when R1 C1 = R2 C2. The frequency at which the circuit oscillates is

$$f = \frac{1}{2\pi\ R1C1}$$

Lamp L_{P1} is a thermistor, in which resistance varies directly with current. It compensates

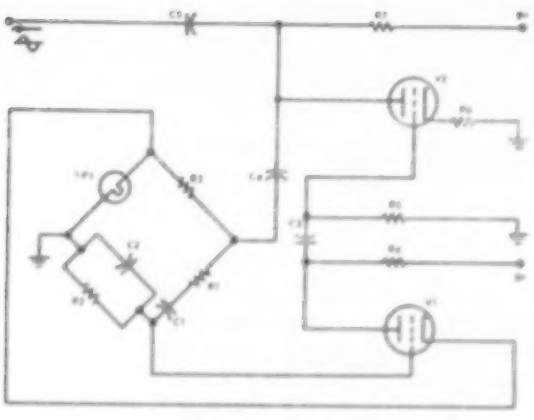


Figure 3-57. Wien bridge oscillator.

automatically for changes in the circuit so that sufficient feedback will always be applied to V2. When current in the circuit increases, the filament of the lamp becomes hotter, making its resistance larger. A greater negative feedback voltage is developed across the increased resistance, and more degeneration is provided that reduces the gain of V1 and hold the output voltage at a nearly constant amplitude.

Crystal-Controlled Oscillators. When the frequency of a transmitter must be held within close limits, a crystal-controlled oscillator is used. This oscillator has a specially cut crystal that controls the frequency. Crystal-controlled oscillators are the standard means of maintaining the frequency of radio-transmitting stations within assigned limits. They are used as a basic circuit to generate an output at a highly stable, accurately measured frequency. Crystals are also used as the active element in high-fidelity microphones, loudspeakers, and electric pickup arms.

Crystals exhibit a characteristic that makes possible their various uses. This characteristic, known as the piezoelectric effect, is the property of a crystal by which mechanical stresses produce electrical charges, and conversely, electric charges produce mechanical stresses. If a voltage is applied to a crystal, it vibrates at its own frequency. The amplitude of vibration of a given crystal is much larger at one frequency than at all others. This is the resonant frequency of the crystal.

This piezoelectric effect is different with crystals of various substances such as quartz, tourmaline, and Rochelle salt. Of the three, Rochelle salt exhibits this effect to the greatest degree. Quartz crystals are used for frequency control in most oscillators because it has greater mechanical strength.

Transmitters that require a very high degree of frequency stability, such as broadcast transmitters, use temperature-controlled ovens to maintain the crystal temperature in the proper range. These ovens are thermostatically controlled containers in which the crystals are placed. Of course, crystals with special cuts are used with a temperature coefficient as close to zero as possible.

Since a vibrating quartz crystal is equivalent to a resonant circuit, it can be used in place of the usual tuned circuit as a frequency-controlling element in an electron tube oscillator. This circuit shown in figure 3-59 represents a common type of crystal oscillator. It is similar to the tuned-plate, tuned-grid oscillator, with the crystal replacing the tuned-grid circuit. The feedback takes place through the plate-to-grid interelectrode capacitance. The oscillations occur at the resonant frequency of the crystal, and the plate circuit is tuned slightly higher, or inductively.

The operation of this circuit is similar to that of the tuned-plate, tuned-grid oscillator. When the filament has heated the cathode to the emission point, the plate voltage is applied and the tube starts conducting. The surge of plate current flowing through L releases energy to the resonant plate circuit and starts it oscillating. The RF voltage developed by the alternating current in the plate tank is applied to the crystal through the plate-to-grid capacitance and the bypass capacitor in parallel with battery.

Placing this voltage across the two plates of the crystal holder causes the crystal to bend physically. When the first surge of plate current is over, the crystal springs back to its normal shape. In doing this, it generates a voltage of its own, causing the grid to become positive. The grid then draws

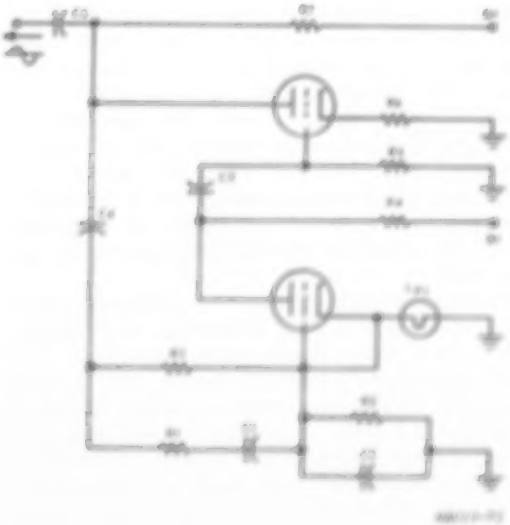


Figure 3-58. Wien bridge oscillator schematic.

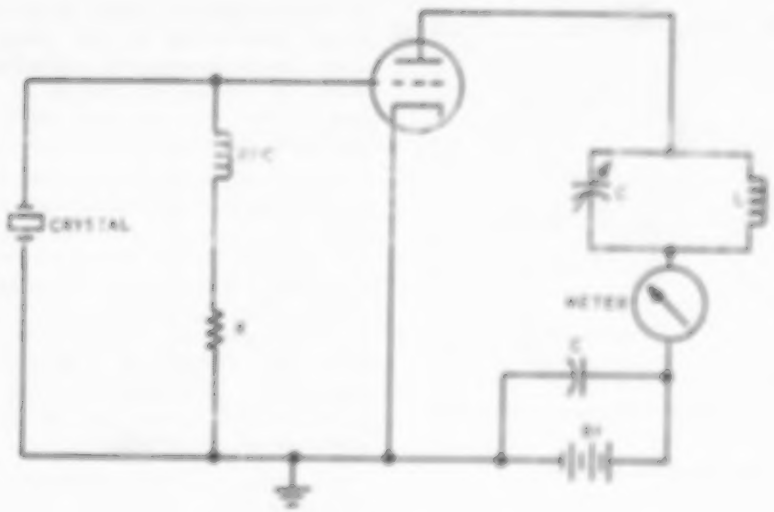


Figure 3-59. Crystal oscillator.

current, becomes negative, and the cycle is repeated. If enough energy is applied back to the circuit in the proper phase to make up for resistive losses, the process continues at the mechanically resonant frequency of the crystal.

A resistor is connected from grid to ground through a choke to allow electrons that have been attracted to the grid on the positive swing to return to the cathode ground. The current flowing through this resistor develops the bias voltage. The capacitor usually associated with the grid-leak resistor is not necessary, because the crystal and holder serve in its place.

A meter is generally used in tuning a crystal oscillator. In figure 3-59, the meter is placed in series with the plate circuit. Direct current flows from the cathode to the plate, then through the meter. Any change in DC plate current is thus shown on the meter. When the oscillator is generating its greatest AC current, the DC bias is maximum. This holds the DC plate current to a minimum, and the meter reading is at a minimum. In tuning, the plate is first tuned for minimum current by adjusting the tuning capacitor in the plate tank.

The power output that can be obtained from a crystal oscillator is limited. If too high an excitation voltage is applied to an active crystal, it may vibrate strenuously enough to shatter itself. For this reason, the triode tube crystal oscillator shown is seldom used. Usually, a pentode or tetrode is used instead, because pentodes and tetrodes are tubes of high-power sensitivity. With them, a comparatively high-power output may be obtained from a small excitation voltage.

This means that only a small amount of excitation voltage is needed to drive the tube to full power output, and a relatively small amount of feedback is enough to meet the requirements for oscillation. The small grid-to-plate capacitance in these tubes offers high impedance to R.F and limits the grid excitation to the small required value. In fact, this feedback by the interelectrode capacitance may be too small, and it may be necessary to add an additional capacitance between the grid and plate.

Exercises (231):

1. What is the minimum number of R-C combinations used to provide feedback in the phase-shift oscillator?

2. Identify the four requirements of all oscillator circuits.

3. What capacitance provides feedback path in the crystal oscillator?

4. Name two R-C-coupled oscillators.

5. When a transmitter frequency has to be held within close limits, what type of oscillator would be used?

Bibliography

[illegible] Courses

CDC 30650, Volume 2, *Electronic Principles, Tools, and Soldering*. Extension Course Institute, Gunter Air Force Station, Alabama.

CDC 32855, Volume 2, *Avionics Fundamentals, Test Equipment, Handtools, and Maintenance Principles*. Extension Course Institute, Gunter Air Force Station, Alabama.

ANSWERS FOR EXERCISES

CHAPTER 1

Reference:

200 –
1. Like charges repel and unlike charges attract.
2. A good conductor has many free electrons and offers little resistance to flow.
3. A good insulator has few free electrons and offers great opposition to electron flow.
4. To oppose current flow.
5. Wire wound.
6. 20 percent.

201 –
1. EMF, potential difference, and voltage.
2. The volt.
3. Ohms, amperes, watts.
4. The watt is a unit of electrical power equal to the work done at the rate of 1 joule per second.
5. The algebraic sum of the applied voltages and the voltage drop around any closed circuit is zero; the algebraic sum of the currents at any junction of conductors is zero; and the amount of current entering a junction equals the amount leaving it.

202 –
1. Current value is the same throughout the circuit.
2. The sum of the voltage drops always equals the applied voltage.
3. 15k ohms, 30k ohms, 60k ohms, and 45k ohms.
4. Total current.
5. It increases total current.
6. It increases total resistance.
7. 85.7k ohms.
8. Add the equivalent resistance of the resistors in parallel to the series resistance.
9. The property of a conductor that enables current to flow.

203 –
1. Permeability is a substance's effectiveness as a path for magnetic lines of force; retentivity is the property that makes it stay magnetized.
2. The magnetism retained after the magnetizing force is removed.
3. The two like poles repel each other.
4. The direction of current through the wire.

204 –
1. The principle that iron is attracted to the pole of an electromagnet.
2. In an automobile starter circuit.
3. As a protective device, similar to a fuse.

205 –
1. Electromagnetic, electrostatic, and electrothermal.
2. A dynamometer.
3. They operate on a heating effect, so they need a warmup.
4. Voltage.
5. Stationary element, moving element, controlling element, moving-element mount with bearings, pointer, scale, and case.

206 –
1. A rectifying circuit.
2. The dynamometer and the iron vane.

207 –
1. A multiplier.
2. To improve scale linearity.

208 –
1. To get more accurate readings on the lower scale.
2. The unknown resistance is in series with the meter.
3. Middle. The scale in this area is more linear.

CHAPTER 2

209 –
1. Peak voltage is 100; effective voltage is 70.7; average voltage is 63.6.
2. The peak voltage is 155.5, and the average voltage is 99.
3. Kilohertz is a thousand cycles per second; megahertz is a million cycles per second.
4. When a waveform's voltage and current aren't moving simultaneously, they're out of phase.

210 –
1. A conductor, a magnetic field, and motion between them.
2. Current flow is at zero.
3. The induced current will be at maximum.
4. The magnetic field's strength, the number of conductors, and the conductors' speed of rotation.
5. Magnetic field coil, pole pieces, slip rings, brushes, armature, and external circuit.

211 –
1. The DC generator uses a commutator in place of slip rings.
2. Series, shunt, and compound.
3. Compound. Adding the series winding to the shunt generator offsets the shunt field's voltage decrease.

212 –
1. The interlocking of magnetic lines of force; the magnetic lines around one coil or wire that link it to another coil or wire.
2. The number of turns in the coil, its diameter, its length, and the type of material in its core.
3. Air.
4. 5.4 henries.
5. The inductor symbol with two parallel vertical lines.
6. Ohms.
7. X.

213 –
1. A core of low-reluctance magnetic material.
2. It has a five-to-one ratio, or a step-down-turns ratio.
3. $\frac{Np}{Ns} = \frac{Ep}{Es}$
4. The extent to which magnetic lines of the primary cut across the secondary.
5. That 90 percent of the lines of flux of the primary winding are cutting the secondary winding.
6. The total primary power equals the secondary power.
7. In a turns ratio transformer, if there's a voltage increase in the primary, there'll be a current decrease, and vice-versa.
8. Autotransformers, power transformers, audio transformers, and RF transformers.

214 –
1. To store electricity.
2. Glass, air, mica, wax paper, or oil.
3. The area of the plates, the distance between them, and the dielectric material.
4. By multiplying the two values and dividing the product by the sum of the capacitive values.
5. The capacitor is charged in one direction and then the other.
6. The opposition the capacitor offers to AC flow. In ohms.

215 –
1. In a resistive circuit, current and voltage are in phase.
2. Impedance.
3. It depends on whether capacitive reactance or inductive reactance is larger.

4. When the frequency decreases, X_L increases and X_c decreases; when it increases, X_L decreases and X_c increases.
5. When capacitive reactance and inductive reactance are equal.
6. An inductive circuit.
7. The ratio of E_L (or E_c) to E_R.
8. In a resistive circuit, current and voltage are in phase; in a capacitive circuit, they're not. Current leads voltage.
9. Current is in phase with voltage.
10. High impedance and minimum line current at resonance.
11. The coil.
12. The frequency and voltage.

CHAPTER 3

216 – 1. Bridge.
2. When V3 is conducting.
3. Figure 3-2.
4. In circuits that need high-circuit currents, because its output is stable under wide current variations (fig. 3-5).
5. The plate must be more positive than the cathode.
6. It is more efficient, has less ripple, and has a wider variety of applications.
7. Two.

217 – 1. e.
2. a.
3. d.
4. b.
5. In low-current installations such as radio receivers.
6. The time constant increases.
7. In circuits requiring large currents.

218 – 1. T.
2. T.
3. T.
4. T.
5. F.

219 – 1. (1) c.
(2) e.
(3) e.
(4) c.
(5) a and e.
(6) e.
(7) d.
(8) c.
(9) e.

220 – 1. a, 200 volts; b, 200 volts; c, 10 mA.
2. a, 100 volts; b, 40k ohms.
3. E_{RL} increases because current doubles and resistance stays the same.
4. $\mu = 13.33$.
5. a. $\mu = 25$; b. $\mu = 10$.

221 – 1. 30 to 15,000 Hz.
2. 10 kHz to 300 GHz.
3. 10 Hz to around 5 MHz.
4. 360°.
5. Half (180°).
6. They produce distortion.
7. Use, frequency response, and class of operation.

222 – 1. (1) b.
(2) a.
(3) c.

223 – 1. C.
2. A.
3. 3. B.

224 – 1. T.
2. T.
3. T.
4. T.
5. T.

225 – 1. (1) f.
(2) c.
(3) e.
(4) a.

226 – 1. To increase bandwidth.
2. Greater amplification with less distortion.
3. The gain control is cathode bias, varied by shifting the operating point on the characteristic curve.
4. Tuned circuits.

227 – 1. Resonant circuits.
2. 100 percent, 50 percent to 75 percent, less than 25 percent.
3. Positive E_{peak} equal to bias.
4. Class A.
5. In the RF range.

228 – 1. In phase.
2. Gain, impedance, and size of cathode resistor.
3. a and b, true, c, false.

229 – 1. High.
2. Negative.
3. Degenerative feedback causing a gain of less than unity.
4. Plate and cathode.
5. Plates.

230 – 1. LC combination.
2. TPTG.
3. Tank circuit.
4. Blocked DC voltage.
5. Interelectrode capacitance.

231 – 1. Three.
2. Power sources, feedback, amplifier, and frequency drive.
3. Plate to grid.
4. Phase shift and Wien Bridge.
5. Crystal controlled.

AUGAPS.AL (864647) 200

☆ U.S. GOVERNMENT PRINTING OFFICE 1986 631-028/40581 Region #4